CHARACTERISTICS OF THE INLAND-ICE OF THE ARCTIC REGIONS.

(PLATES XXVI–XXX.)

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(Read April 22, 1910.)

CONTENTS

The Arctic Glacier Type.

Introduction.—As elsewhere pointed out, continental glaciers are in other than dimensional respects sharply differentiated from those types which have been described as mountain glaciers.[1] The ice-cap glacier, while of smaller dimensions than the true inland-ice or the continental glacier, is yet distinctly allied with this type, and has few affinities with mountain glaciers. The sharpness of the distinction has often been overlooked for the reason that true mountain glaciers frequently exist within a fringe surrounding the larger areas of inland-ice both in the Arctic and Antarctic regions. The distinguishing difference between mountain glaciers and continental glaciers is one primarily dependent upon the proportion of the land surface which is left uncovered by the ice, and the position of this surface relative to the margins of the snow-ice mass. *With true mountain glaciers land remains uncovered above the highest surfaces of the glacier, where, in consequence, a special erosional process—cirque recession—becomes operative.* The smaller ice-caps take their characteristic carapace form and cover the surface of the land within their margins, because that surface is relatively level. Had it been otherwise, the same conditions of precipitation would have yielded mountain glaciers in their place. The law above stated is none the less applicable, since because of this flat basement no land projects above their higher levels.[2]

[1] Wm. Herbert Hobbs, "The Cycle of Mountain Glaciation," *Geogr. Jour.*, Vol. 35, 1910, pp. 147, 148.

[2] With a keenness of insight which has rendered the descriptions of his travels particularly valuable, Sir Martin Conway has pointed out the main distinction here expressed. His explanation of cirque formation, which he

There are, as we shall see, other attributes which strikingly differentiate the large continental glaciers from all other bodies of land ice. These relate particularly to the nature of the snow which feeds them, to changes which that snow undergoes after its fall, to the manner of its transportation, etc. Most of these differences are of such recent discovery, or at least of such recent introduction into the channels of dissemination of science, that they have not yet found their way to the student of glacial geology. We shall profitably begin our description of continental glaciers with the intermediate ice-cap type, so as to establish connection with mountain glaciers in the important condition of alimentation. Before doing so, it will be well to call attention to some contrasts which exist between the north and south polar regions in those conditions upon which glaciation depends.

North and South Polar Areas Contrasted.—A glance at a globe, which sets forth the land and water areas of the earth, is sufficient to show that the disposition of land and water about the opposite ends of the earth's axis is essentially reciprocal. About the north pole we find a polar sea, the Arctic Ocean, surrounded by an irregular chain of land masses which is broken at two points, nearly diametrically opposite. In the Antarctic region, on the contrary, it is a high continent which surrounds the pole, and this is bounded on all sides by a sea in which are joined all the great oceans of the globe. This polar continent is deeply indented on two nearly opposite margins, but to what extent is not yet known. The margins of the continent are extended beneath the sea in a wide continental shelf or platform. The broad encircling ocean, while to some extent invaded by the southern land tongues of South America, Africa, Australia and New Zealand, is yet so little occupied by land masses that wind and ocean currents are alike but slightly affected by them. The Antarctic conditions are, therefore, oceanic—characterized by uniformity and symmetry to a much larger extent than is true of the northern polar region.

clearly recognized to be a result of sub-aerial disintegration rather than erosion, is however, practically that advanced by Richter, since it takes no account of the bergschrund. (W. M. Conway, "An Exploration in 1897 of some of the Glaciers of Spitzbergen," *Geogr. Jour.*, Vol. 12, 1898, pp. 142–147.)

Within the northern hemisphere a large quantity of heat from the tropics finds its way northward to the breaks in the northern land chain, through the medium of great ocean currents—the Gulf Stream in the Atlantic, and the Japanese Current in the Pacific. Cold return currents from the Arctic region, and the widely different specific heats of land and water, coöperating with the effect of the northward flowing warmer currents, result in a marked diversity in temperature, winds and precipitation at different longitudes within the same latitudes. Lack of symmetry in distribution and wide variations in climatic conditions are, therefore, characteristic of the north polar region; and it follows that the present glaciation of the northern hemisphere is localized within a few scattered areas where the land projects farthest toward the pole and near where there are sea areas of excessive evaporation to supply the necessary moisture.

The Fixed Areas of Atmospheric Depression.—Examination of Fig. 1 will show that the areas of existing heavy glaciation in the northern hemisphere lie close to the so-called fixed areas of low barometric pressure, each of which is a long, curved trough, concave to the northward, one central over the Aleutian Islands' Arc at the northern bay of the Pacific Ocean, the other extending from the southeastern extremity of Baffin Land past Cape Farewell, and northeastward across Iceland, so as to occupy similarly the northern bay of the Atlantic Ocean. For such northern latitudes these areas of fixed low barometric pressure are in consequence characterized by abnormally large evaporation. Wherever the moisture-laden winds proceeding from these areas are forced to rise by upland barriers, or to come in contact with cold rock or snow surfaces, condensation and precipitation must inevitably take place.

The prevailing westerly winds from the Pacific, when they encounter the high backbone of the Cordilleran System of mountains in Alaska nourish the great mountain glaciers of that region. The Cordilleras of Alaska are, however, competent to arrest but a small portion of these moisture-laden clouds, for it is only in moderate latitudes that they bar the way, and no highlands lie beyond them to the eastward until the vicinity of Baffin Bay has been reached.

On the border of the Atlantic low pressure area are found Greenland, Iceland, Spitzbergen, Norway, Franz Josef Land and Nova Zembla, each with its upland areas and its existing glaciation. In Norway, Iceland, and Franz Josef Land we find ice-caps; in Spitzbergen, Nova Zembla, Baffin Land, Grinnell Land and Ellsmere Land, the mantle of snow and ice is best described by the

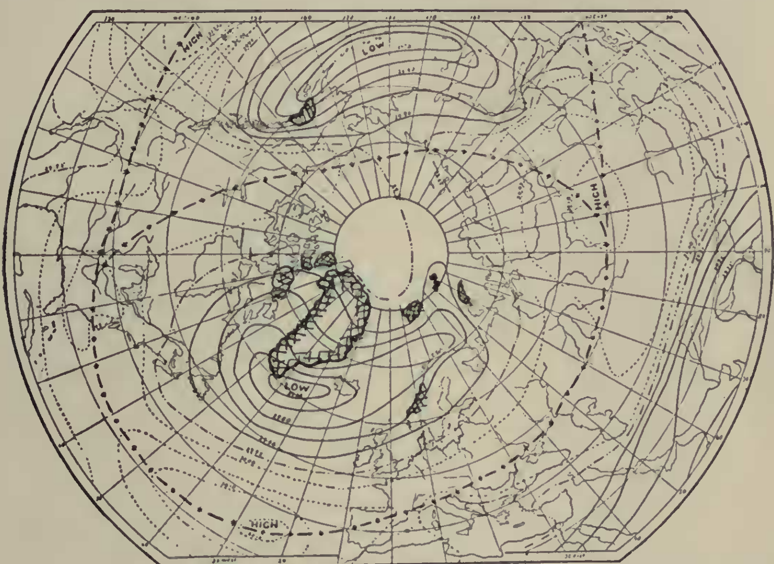

Fig. 1. Map showing the areas of fixed low barometric pressure in the northern hemisphere (after Buchan). The areas of heavy glaciation have been added.

name inland-ice, while upon the continent of Greenland the inland-ice has continental dimensions and forms one of the two continental glaciers that still exist.

Of all the northern ice sheets, with the exception of the Archipelago of Franz Josef Land, the rule holds that they are smaller than the land masses upon which they rest, and this in part expresses the difference between the northern and southern types of inland-ice.

Ice-caps of Norway.—In contrast with all save the Piedmont type of mountain glaciers, the snow fields of ice-caps are much the larger. Speaking broadly, high and relatively level plateaus, light winds, and low temperatures are favorable to the existence of ice-caps. Today they are not to be found in latitudes lower than 60°. In Norway, within the zone of heavy precipitation along the western coast, and upon the remnants of the plateau separated by the fjords, are still to be found a number of small ice-caps. These caps consist of a central carapace of snow and ice from the borders of which narrow tongues descend into the fjords. The largest of these ice-caps is the Jostedalsbraen, having an area of 1,076 square kilometers. Whereas with mountain glaciers the névé is contained within a basin, the cirque, we here find the so-called "fjeld" nearly level and resting upon the surface of the plateau. Of this fjeld broadly lobate extensions lie upon its margin separated by deep valleys or fjord heads. Much narrower extensions of the central carapace often descend the steep slopes at the upper end of these valleys and may continue down the valley floor. Their narrowness is largely explained by their more rapid motion upon the steeper slope and by the reflected heat from the rock walls on either side. See Fig. 2.[3]

FIG. 2. Idealized section showing the form of "fjeld" and "brae" in Norwegian ice-cap.

Ice-caps of Iceland.—In Iceland are to be seen some of the finest examples of ice-caps that are known, and, fortunately, these have been carefully studied by Thoroddsen.[4] These ice-caps form gently domed crests or undulating ice fields situated upon the

[3] H. Hess, "Die Gletscher," 1904, pp. 66, 99–92.

[4] Th. Thoroddsen, "Island, Grundriss der Geographie und Geologie," *Pet. Mitt.* (Ergänzungshefts 152, 153), 1906, V., "Die Gletscher Islands," pp. 163–208.

highest plateaus which rise above the general table-land of the country. Projecting mountain peaks appear with few exceptions only near the thinnest margins of the ice, where they form either comb ridges or sharp peaks (see Figs. 3 and 4). White and altogether free from surface rock débris except in the vicinity of their margins, these ice-caps offer in this respect additional contrast to mountain glaciers. The largest of the Iceland ice-caps is the Vatna Jökull, which has an area of 8,500 square kilometers,

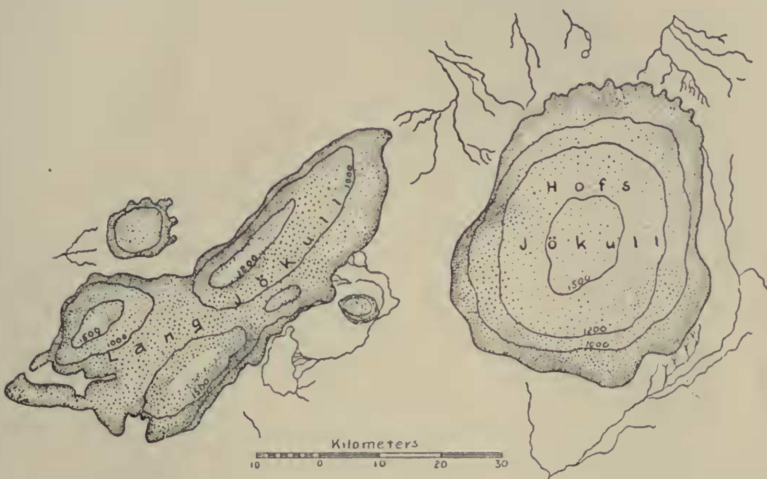

FIG. 3. Maps of the Hofs Jökull and the Lang Jökull (after Thoroddsen).

while the surfaces of the Hofs Jökull, Lang Jökull and Myrsdals Jökull each exceed a thousand square kilometers. The shield-like boss of the Vatna Jökull is brought out in the section of Fig. 5.[5]

Those borders of this ice mass which lie upon the plateau, the northern and western areas, are broadly lobate; but upon the southern and eastern margins, where the ice mass descends to lower levels and approaches the sea, its tongues sometimes end a few meters only above sea level. It is noteworthy, however, that where deeply incised valleys invade the plateau upon this margin, the lobes of ice push out mainly upon the upland remnants between

[5] Hans Spethmann, "Der Nordrand des isländischen Inlandeises Vatnajökull," *Zeitsch. f. Gletscherk.*, Vol. 3, 1909, pp. 36–43.

the valleys, though they send narrow tongues down the valleys themselves. This, as we shall see, is a peculiarity which ice-caps and the northern inland-ice as well have in common to distinguish

FIG. 4. Map of the Vatna Jökull (after Thoroddsen).

them further from mountain glaciers. As was found true of the Norwegian glaciers, so here the tongue which follows the valley bottom and which partakes of many of the properties of a mountain glacier, is much the narrower.[6]

From the north or plateau margin of the Vatnajökull flow mighty but sluggish streams which near the glacier are braided into constantly shifting channels within a broad zone of quicksand. In this sand, horse and rider if once entangled are quickly lost. Upon the south margin, on the other hand, the streams from the melt-

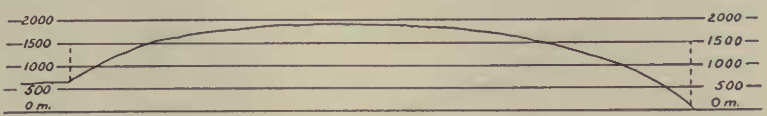

FIG. 5. Cross section of the Vatna Jökull from north to south (after Thoroddsen and Spethmann).

ing of the ice flow as fast rushing rivers, sometimes so broad as not to be bridged, and in these cases setting up impassable barriers between districts.

Icelandic ice-caps differ from all well-known glaciers at least in this, that nowhere else are large ice masses in such direct association with so active volcanoes. The *jökulhlaup,* which is the Icelandic name applied to one of the characteristic catastrophies of the island, occurs whenever a volcano, either visible in the neighborhood of the glacier or hidden beneath it, breaks suddenly into eruption. The first intimation that such an event is transpiring, is often the drying up of a stream which flows from the affected region. Sometimes the people are permitted to see great masses of lava and volcanic ash issue together from the glacier. All at once, the stream which had first dried up comes rushing down its valley as a foaming flood of water, spreading out for miles and having a depth sometimes as great as 100 feet. The entire plain is then spread with mud and sown with great rocks and also with ice blocks, some of which are as large as the native houses. These ice blocks are

[6] Carl Sapper, "Bemerkungen über einige südisländische Gletscher," *Zeitsch. f. Gletsch.,* Vol. 3, 1909, pp. 297–305, two maps and three figures. See especially Fig. 3.

often buried in the mud, and later, when they have melted, they leave deep pits in the plain similar to though smaller than the depressions in a "pitted plain" from the continental glaciers of Pleistocene time.

During such an eruption, water has been seen to shoot up from the glacier in great jets, and it has sometimes happened that the entire ice mass of the jökul has been shattered, and a chaotic mass of ice miles in width has slipped resistlessly down the slopes. With the conclusion of the disturbance, the aspect of the entire district is sometimes found to be utterly changed. All vegetation has been destroyed, and ridges which had lent to the landscape its character have vanished, so that streams have lost their old channels and entered upon wholly different courses.[7]

Ice-covered Archipelago of Franz Josef Land.—The islands of Franz Josef Land in the high latitude of 80° and over, with altitudes of 2,000 to 4,000 feet and situated as they are on the borders of an open sea, are the most Arctic in their aspect of all the smaller northern land masses. As a consequence, they are with unimportant exceptions completely snow capped, the snow-ice covering sloping regularly into the sea upon all sides. The Jackson-Harmsworth[8] and Ziegler[9] expeditions, following those of Nordenskiöld, Nansen, the Duke of the Abruzzi, and others, have now supplied us with fairly accurate maps of all islands in the archipelago. One or two of the western islands alone show a narrow strip of low shore land, but with these exceptions all are covered save for small projecting peaks or plateau edges near the ice margins (see Fig. 6). They present, therefore, a unique exception to the law which otherwise obtains, that within the northern hemisphere glacial caps are smaller than the land areas upon which they rest. The appearance of the island covers is here, however, that of névé of low density, rather than of compact glacier ice.

Prince Rudolph Island, which was the winter station of the Italian polar expedition, is no doubt typical of most islands in the

[7] Otto Nordenskiold, "Die Polarwelt," 1909, pp. 42–43.

[8] F. G. Jackson, "A Thousand Days in the Arctic," 1899, map 5.

[9] Anthony Fiala, "The Ziegler Polar-Expedition of 1803–5," 1907, map C.

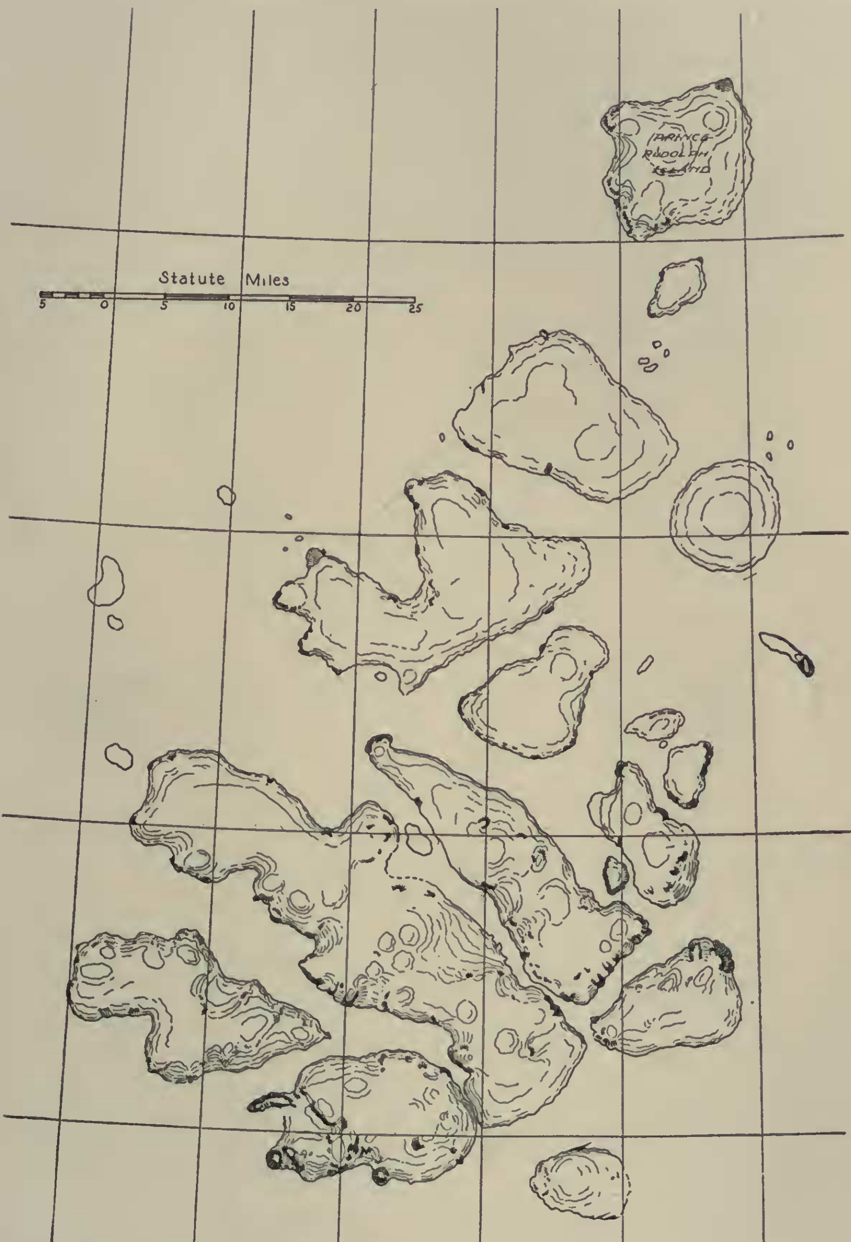

FIG. 6. Map of the ice-capped islands in the eastern part of the Franz Josef Archipelago (after Fiala).

archipelago. This island is described by Duc d'Abruzzi[10] as "completely buried under one immense glacier, which descends to the sea in every direction except at a few points, such as Cape Germania, Cape Säulen, Cape Fligely, Cape Brorok, Cape Habermann and Cape Auk. At some of these points, . . . the coast is almost perpendicular, which prevents the ice from descending to the sea. At others, . . ., the ice, stopped by a hollow, falls into the sea on each side of the headland, which thus remains uncovered. Moreover, wherever the snow can rest, there are glaciers which end at the sea in an ice-cliff, like that formed by the main glacier, so that it can be said that the entire coast, with the exception of a short extent of strand near Teplitz Bay, is formed by a vertical ice-cliff" (see Fig. 7).

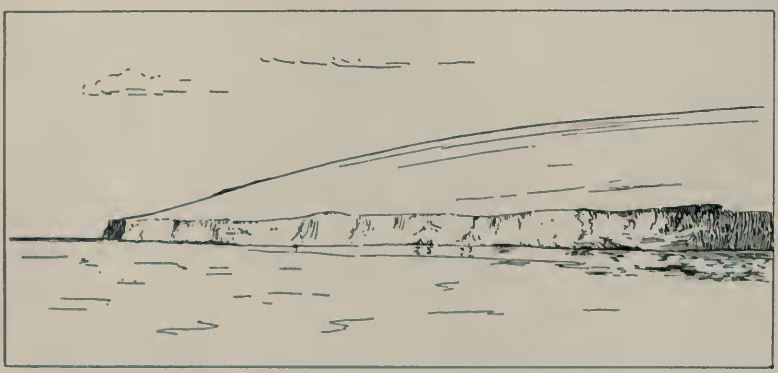

FIG. 7. Typical ice cliff of the coast of Prince Rudolph Island, Franz Josef Land (after the Duke of the Abruzzi).

The movement of the ice is so slow that though a line of posts was established for the purpose of measuring during a period of four months, no movement could be detected. Except near the outermost margin, there were few crevasses, and these were covered by snow. In summer, on days when the temperature was above the freezing point, the snow thawed rapidly so that torrents of water flowed from the glacier to the sea, hollowing out channels many feet in width.

During the stay of the "Polar Star" near the island, it was

[10] On the "Polar Star" in the Arctic Sea, 1903, Vol. 1, pp. 116–118.

noteworthy that thaw and evaporation upon the island exceeded the precipitation. Doubtless because of the slow movement of the ice, no icebergs were seen to form during the entire stay.

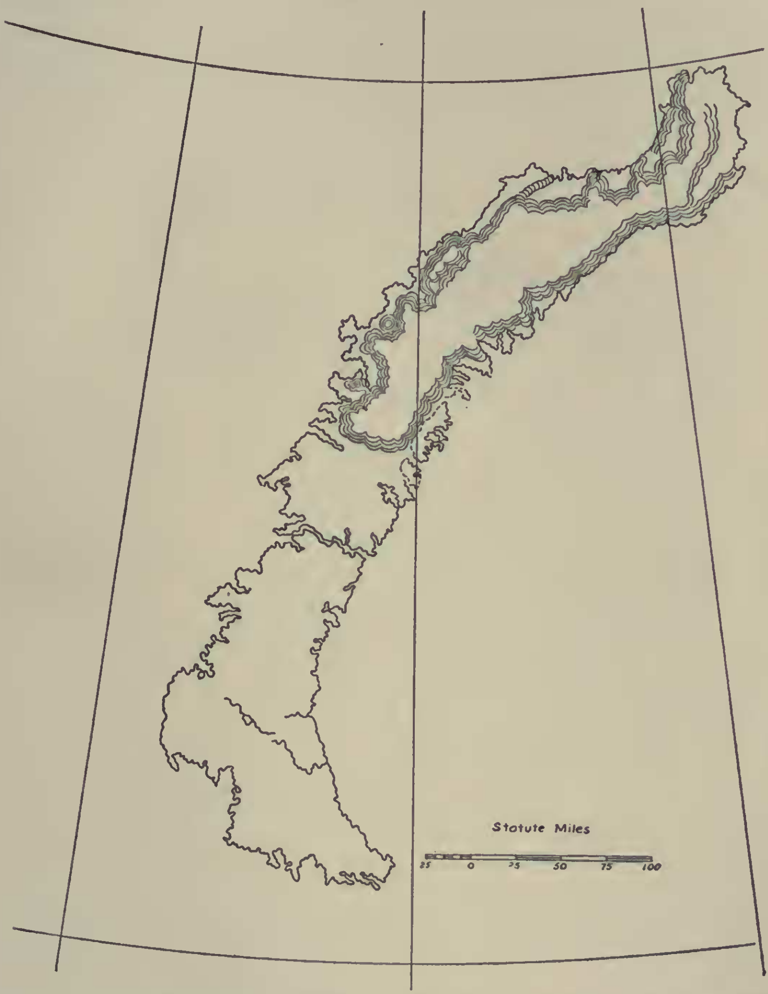

Fig. 8. Map of Nova Zembla, showing the supposed area covered by inland-ice (from Andree's "Handatlas").

The Smaller Areas of Inland-ice Within the Arctic Regions.—The ice-cap of the Vatna Jökull in Iceland, which is the largest to which this name has been applied, covers an area of 8,500 square kilometers. Ice carapaces which are better described as inland-ice, since they cover considerable proportions of the interiors of the land areas upon which they rest, occur to the northward of Europe in Nova Zembla and Spitzbergen, and in the lands to the west of Baffin's Bay, known as Baffin, Ellesmere, and Grinnell lands.

FIG. 9. Map of Spitzbergen, showing the supposed glaciated areas (from Andree's "Handatlas").

Nova Zembla is a long, narrow island, stretching between 70° and 84° of north latitude (see Fig. 8). It is in reality two islands separated by a narrow strait near the latitude of 76°. The northern island, which to the north is a plateau attaining an altitude of 1,800 feet, appears to be in large part covered by inland-ice, though it has been as yet but little explored.

The Inland-ice of Spitzbergen.—The group of islands to which the name Spitzbergen has been applied, lies between the parallels of 76° and 81° of north latitude. The surface is generally mountainous, the highest peaks rising to an elevation of about 5,000 feet, though the greater number range from 2,000 to 4,000 feet in altitude. The large northeastern land mass is called North East Land and is covered with inland-ice which was crossed by Nordenskiöld and Palander in 1873[11] (see Fig. 9). New Friesland, or the northeastern portion of the main island, is also covered by inland-ice[12] (see Fig. 10). The southwestern margin of this inland-ice was

FIG. 10. Inland-ice of New Friesland as viewed from Hinloopen Strait (after Conway).

somewhat carefully mapped by Conway and Gregory in 1896,[13] and as this presents some interesting general features, it is reproduced in part in Fig. 11.

In addition to the lobes which push out upon the crest of the plateau, there is here an expansion laterally beyond the main cap and at lower levels in the form of an apron which is called the Ivory Gate (compare the Frederikshaab Glacier in Fig. 38, p. 119). Surrounding the inland-ice to the westward are small ice-caps resembling the fjelds and braes of Norway, and also true mountain glaciers whose cirques have shaped the mountains into the sharp pinnacles of comb ridges. It is to these sharp peaks that Spitzbergen owes its name.

[11] A. E. Nordenskiold, "Grönland" (authorized German edition), map on p. 141.

[12] W. Martin Conway, "An Exploration in 1897 of some of the Glaciers of Spitzbergen," *Geogr. Jour.*, Vol. 12, 1898, pp. 137–158.

[13] Sir Wm. Martin Conway, "The First Crossing of Spitzbergen," London, 1897, pp. 371, 2 maps.

In the year 1890 Gustav Nordenskiöld made a journey between Horn Sound and Bell Sound on the west coast, and found behind the sharp peaks bordering the coast an ice surface almost without crevasses or nunataks.[14] Upon the northwest coast no sharp peaks or comb-ridges are found, but there is a low plateau with deep, narrow valleys similar to the west coast of Norway where it

FIG. 11. Map of the southwestern margin of an extension of the inland-ice of New Friesland (after Conway).

reaches the sea near the North Cape. All the rock surfaces are glaciated.

The inland-ice of North East Land reaches the sea upon the southern and eastern coasts, but is surrounded by a hem of land upon the north and west. Over the surface of this ice Nordenskiöld

[14] O. Nordenskiöld, *l. c.*, p. 52.

observed that the snow does not melt even in midsummer, and that hence there were developed no lines of surface drainage. Of especial note were the great crevasses which ran generally in straight lines for long distances in parallel series, sometimes two interesting series being observed. More remarkable than these, however, were the so-called "canals," which also for the most part ran parallel to each other and in some cases were only 300 feet apart. These

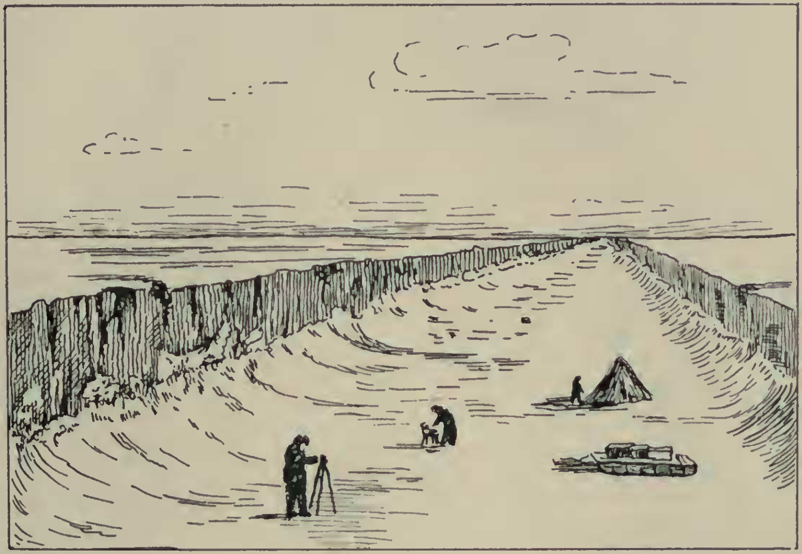

FIG. 12. Camping place in one of the "canals" upon the surface of the inland-ice of North East Land, Spitzbergen (after Nordenskiöld).

canals, which were found in the southeastern part of the area near Cape Mohn, were in reality deep, flat-bottomed troughs within the ice, bounded on either side by parallel and rectilinear ice cliffs, and were in places partially filled by the indrifted snow. Stretching for long distances over the snow plain, and set so deeply that they could be entered only where fortuitous drifting of the snow supplied an incline, they were utilized for camping places (see Fig. 12).

Nordenskiöld has explained these canals as trough faults within the ice, and has assumed that this deformation was due to changes of volume incidental to extreme temperature range (see Fig. 13). This explanation in temperature changes would leave the absence of such structures in other places wholly unaccounted for, and we venture to believe that a recent trough faulting within the rock basement below the ice and communicated upward through it, would furnish a more reasonable assumption, particularly in view of our later knowledge of dislocations connected with earthquake disturbances.

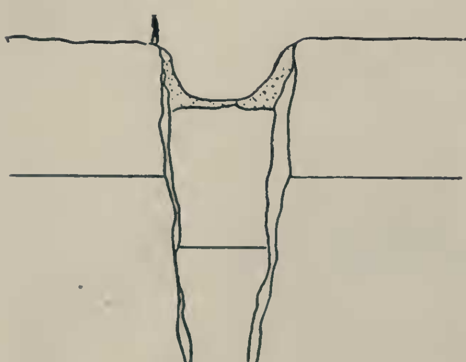

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FIG. 13. Hypothetical cross section of a glacial canal upon the inland-ice of North East Land (after Nordenskiöld).

FIG. 14. Map showing the supposed area of inland-ice upon Grinnell and Ellesmere Lands (from Andree's "Handatlas").

Still deeper in-breaks of the ice were encountered within the same region. These, though deeper, were generally of less extent, and were designated by the sailors of the party "docks" or "glacier docks."

The Inland-ice of Grinnell, Ellesmere and Baffin Lands.—Something has been learned of the inland-ice of Grinnell Land (see Fig. 14) from the report of Lieutenant Lockwood upon his crossing of Grinnell Land in 1883.[15] Of especial interest is his description of the ice front or face as it was observed for long distances

[15] A. W. Greely, "Report on the Proceedings of the United States Expedition to Lady Franklin Bay, Grinnell Land," Vol. 1, especially Appendix No. 86, pp. 274–279, pls. 1–4. See also Salisbury, Jour. Geol., Vol. 3, p. 890.

in the form of a perpendicular wall which he described under the name "Chinese Wall." Over upland and plain this wall extended with little apparent change in its character. At one place by pacing and sextant angle its height was estimated at 143 feet (see Fig. 15).

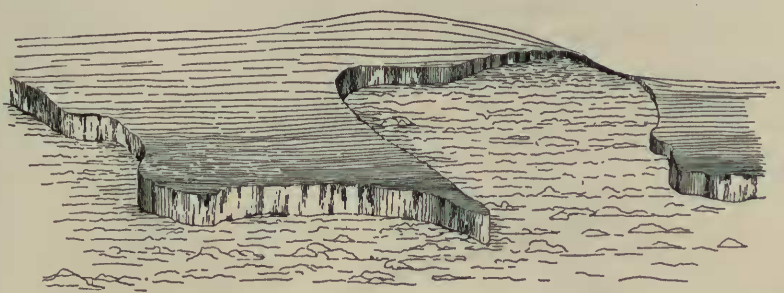

Fig. 15. View of the "Chinese Wall" surrounding the Agassiz Mer de Glace on Grinnell Land (after Greely).

The inland-ice of Ellesmere Land (see Fig 14) has been to some extent explored along its borders by members of the Sverdrup expedition. The maps of the margin in the vicinity of Buchanan Bay display much the same characters as may be observed along the margins of the better known ice-caps and inland-ice masses of the northern hemisphere.[16]

Of the inland-ice of Baffin Land little is known (see Fig. 16). There are some indications that a small ice-cap exists upon the neighboring island of North Devon.

Physiography of the Continental Glacier of Greenland.

General Form and Outlines.—The inland-ice of Greenland, we have now good reason to believe, has the form of a flat dome, the highest surfaces of which lie somewhat to the eastward of the medial line of the continent,[17] and which envelops all but a relatively narrow marginal rim. This marginal ribbon of land is usually from five to twenty-five miles in width, may decrease to noth-

[16] Otto Sverdrup, "New Land," 2 vols., London, 1904, pp. 496–504.

[17] F. Nansen, "The First Crossing of Greenland," Vol. 2, p. 404; R. E. Peary, "Journeys in North Greenland," *Geogr. Jour.*, Vol. II., 1898, p. 232.

ing, but in two nearly opposite stretches of shore it widens to from sixty to one hundred miles (see Fig. 17).

At the heads of many deep fjords long and narrow marginal tongues pushing out from the central mass reach to below sea level; and within three limited stretches of shore the ice mantle overlaps the borders of the continent and reaches the sea in a broad front.

FIG. 16. Map showing the supposed area of inland-ice upon Baffin Land (from Andree's "Handatlas").

The longest of these begins near the Devil's Thumb on the west coast at about latitude 74′ 30″, and extends with some interruptions for about one hundred and fifty miles along the coast of Melville Bay.[18] Where crossed by Nansen near the parallel of 64°, and hence near the southern margin, and also where traversed by Peary near its northwestern borders, the inland-ice has revealed much

[18] T. C. Chamberlin, "Glacial Studies in Greenland," III., *Jour. Geol.*, Vol. 3, 1895, pp. 62–63.

the same features. The great central area has never been entered, although Baron Nordenskiöld and Lieutenant Peary, as well as Nansen, have each passed somewhat within the margin near the

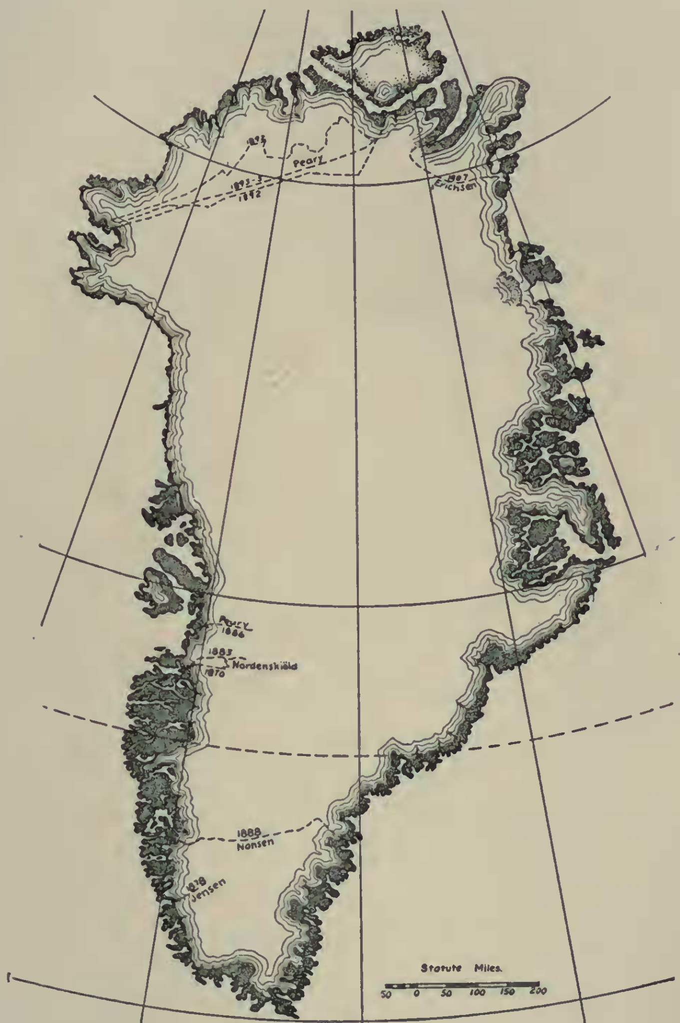

FIG. 17. Map of Greenland, showing the outlines of the inland-ice (from Andree's "Handatlas," but corrected for the northeast shore from data of the Danish expedition of 1908). The routes of the various expeditions on the inland-ice have also been added.

latitude of 68°. More recently (1907) Mylius Ericksen met his tragic death in crossing the inland-ice in northeast Greenland, but his results, most fortunately recovered, are not yet published. Yet such is the monotony of the surface thus far revealed, and such the uniformity of conditions encountered, that there is little reason to think future explorations in the interior will disclose anything but a desert of snow with such small variations from a horizontal surface as are not strikingly apparent to the traveller at any one observing point.

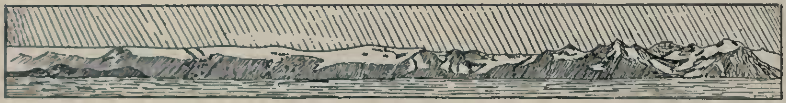

FIG. 18. Sketch of the east coast of Greenland near Cape Dan. Shows the inland-ice and the work of marginal mountain glaciers (after Nansen).

Nansen has laid stress upon the close adherence of the curve of his section to that of a circle, and has attempted to apply this interpretation to the sections of both Nordenskiöld and Peary made near the latitude of Disco Bay.[19] If the marginal portions of the sections be disregarded, this interpretation is possible for Nansen's own profile, since it is in any case very flat; but inasmuch as the margins only were traversed in the other sections, the conclusions drawn from them are likely to be misleading when extended into the unknown interior.

Hess,[20] correcting Nansen's data so as to take account of the curvature of the earth, finds the radius of this circle of the section to be approximately 3,700 km. (instead of 10,380 km., as given by Nansen). This radial distance being considerably less than the average for the earth's surface, the curvature of the ice surface where crossed by Nansen is considerably more convex than an average continental section.

We are absolutely without knowledge concerning either the thickness of the ice shield or the elevation of the rock basement

[19] H. Mohn und Fridtjof Nansen, "Wissenschaftlichen Ergebnisse von Dr. F. Nansens Durchquerung von Grönland, 1888," *Pet. Mitt. Ergänzungsh.*, 105, 1892, pp. 1–111, 6 pls., 10 figs. Especially Plate 5.

[20] "Die Gletscher," pp. 105–106.

beneath it; though a height of the snow surface of approximately 9,000 feet was reached by Nansen at a point where it could hardly be expected to be a maximum. The snow surface to the north of his section was everywhere rising, and it is likely that it attains an altitude to the northeastward well above 10,000 feet.

Though doubtless almost flat within its central portions, and only gently sloping outward at distances of from seventy-five to one hundred miles within its margin, the snow surface falls away so abruptly where it approaches its borders as to be often quite difficult of ascent (see Fig. 19).[21] The monotony of the flatly arched cen-

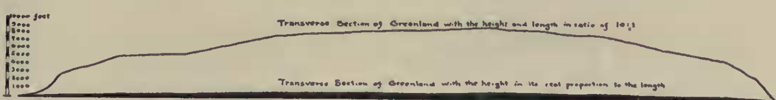

FIG. 19. The section across the inland-ice of Greenland, near the 64th parallel of latitude in natural proportions and with vertical scale ten times the horizontal (after Nansen).

tral portion of the isblink gives place to wholly different characters as the margins are approached. The ice descends in broad terraces or steps, which have treads of gentle inclination but whose risers are of greater steepness, and this steepness is rapidly accelerated as the margin is neared. In Fig. 20 have been placed together for comparison the profiles of Peary, Nordenskiöld and Nansen on the different routes which they travelled toward the interior from the coast.

The margins of the Greenland continent where uncovered by the ice, are generally mountainous, with heights reaching in many cases to between 5,000 and 8,000 feet on the east shore[22] and between 5,000 and 6,000 feet on the west shore. The bordering ice-caps within these areas are developed in special perfection on the islands of the archipelago about King Oscars fjord and Kaiser

[21] R. E. Peary, "A Reconnoissance of the Greenland Inland-ice," *Jour. Am. Geogr. Soc.*, Vol. 19, 1887, pp. 261–289.

[22] Petermann Peak near Franz Josef fjord on the east coast, which according to Nansen has an estimated height of 11,000–14,000 feet, has recently been shown to be not more than half that height (A. G. Nathorst, *Pet. Mitt.*, Vol. 45, 1899, p. 242).

Franz Josef fjord on the east coast near latitude 75° N., as these have been mapped by the Swedish Greenland Expedition of 1899 (see Fig. 21).[23] The work of mountain glaciers about King Oscars fjord is clearly displayed by Nathorst's photograph reproduced in Plate XXVI, *A*. Essentially the same features are shown also to the right in Fig. 18 (p. 78).

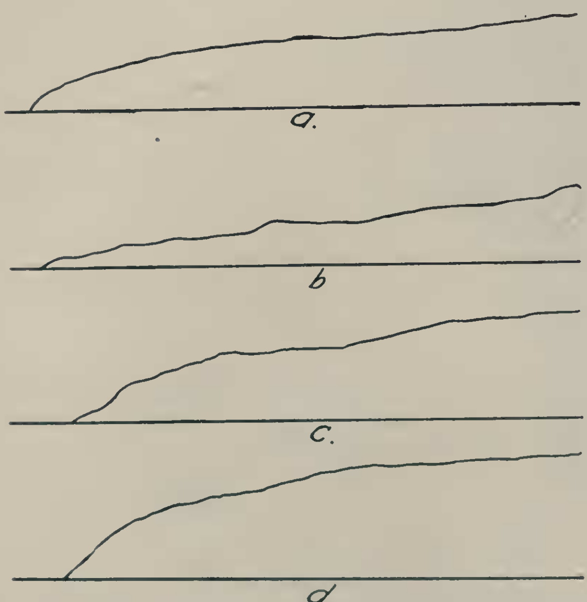

FIG. 20. Comparison of the several profiles across the margin of the inland-ice (*a*) at latitude 69 1/2° on the west coast (Peary); (*b*) at latitude 68 1/2° on the west coast (Nordenskiöld); (*c*) at latitude 64° on the west coast (Nansen); and (*d*) at latitude 64 1/2° on the east coast (Nansen).

While we are without absolute knowledge of the relief of the land beneath most of the inland-ice, we know that the mountainous upland of the coast extends well within the ice margins, since the peaks project through the surface as ice-bounded rock islands or *nunataks*. The irregularities of this basement and the submergence and consequent drowning of the valleys to form deep fjords within the marginal zones, largely account for the markedly lobate out-

[23] A. G. Nathorst, "Den svenska expeditionen till nordöstra Grönland," 1899, *Ymer*, Vol. 20, 1900, map 11.

lines of the so-called isblink[24] or inland-ice, as well as for the ice-caps and mountain glaciers, which originating in the outlying plateaus and mountains, form a fringe about the central ice mass.

It has been shown to be characteristic of the ice-caps and smaller inland-ice areas of the Arctic region outside of Greenland, that their lobate margins are in part accounted for by extensions of the

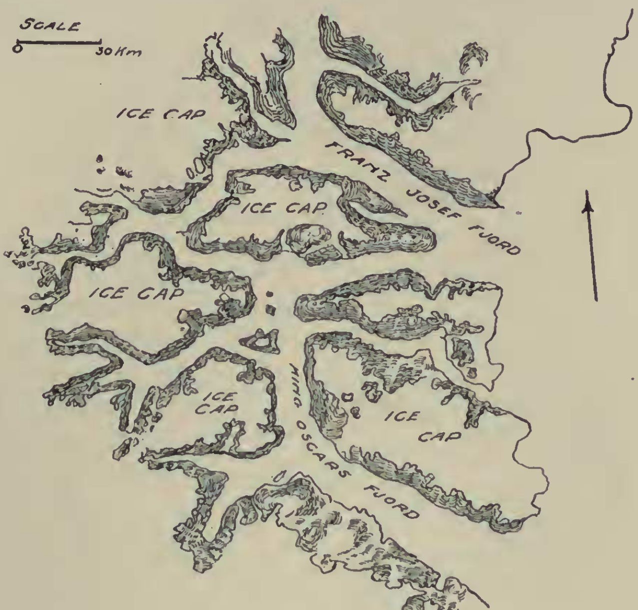

FIG. 21. Map of the region about King Oscars and Kaiser Franz Josef fjords, Eastern Greenland, showing the areas of the numerous ice-caps (after P. Dusen).

cap upon the plateau between intersecting valleys or fjords, as well as by extensions down these valleys. These latter extensions of the ice sheets are, however, much the narrower. Identically the same features are found to characterize the Greenland inland-ice as well. The manner in which this occurs in Greenland has been

[24] "Iceblink," which has been suggested by some writers, is a term generally applied among navigators to describe the appearance of ice on the horizon, and is contrasted with "land blink," which describes the peculiar loom of the land. In order to apply the term to the inland-ice without confusion, it is, therefore, better to retain the Danish form of the word.

well brought out in a map and section by Helland[25] of the Kangerdlugsuak fjord and glacier, but even better by recent maps of the

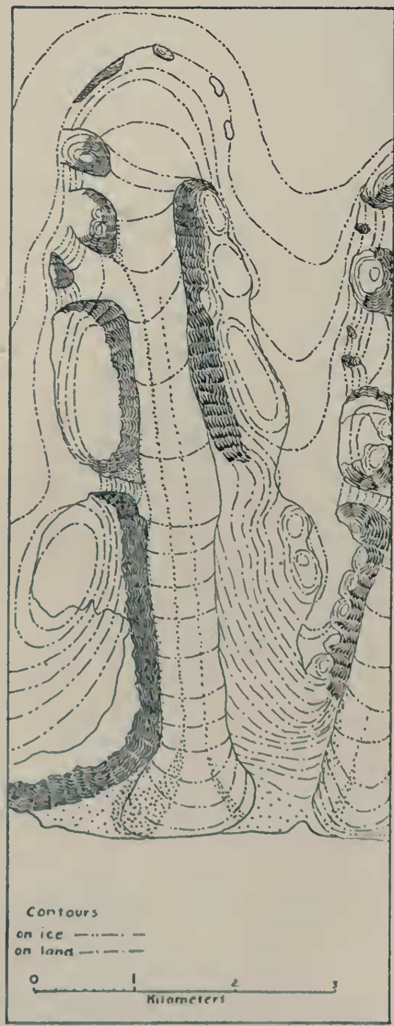

FIG. 22. Map of a glacier tongue, which extends from the inland-ice down the Umanak fjord (after von Drygalski).

[25] A. Helland, "On the Ice Fjords of North Greenland and on the Formation of Fjords, Lakes, and Cirques in Norway and Greenland," *Quart. Jour. Geol. Soc.*, Vol. 33, 1877, pp. 142–176.

Petermann Fjord by Peary (Fig. 25, p. 89) and the Umanak fjord by von Drygalski[26] (see Fig. 22). The manner in which the ice sometimes descends from the higher levels over the steep walls of the fjords has been strikingly brought out in a photograph of the Foetal glacier (see Fig. 23).[27]

As already stated, within one limited stretch upon the west coast the ice mantle overlaps the borders of the continent and reaches

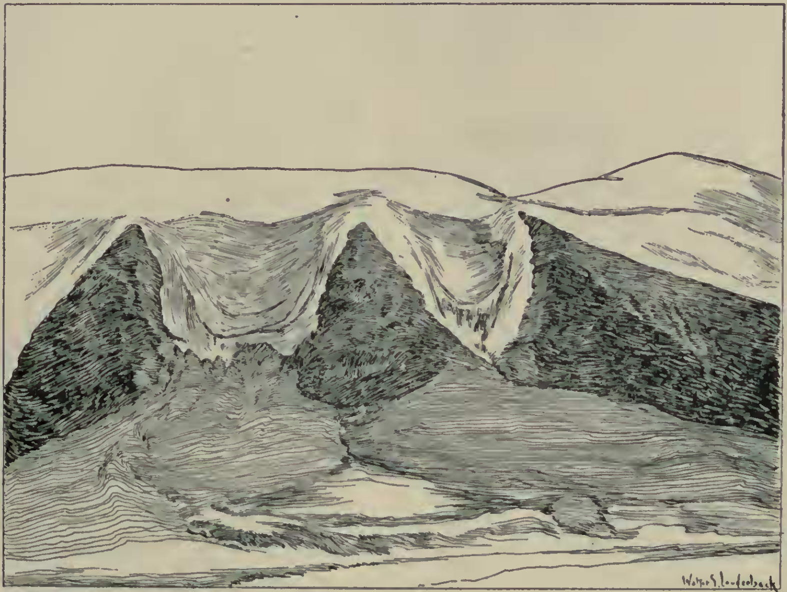

FIG. 23. Tongues of ice descending from the Foetal glacier, McCormick Bay (after Peary).

the sea in a broad front. This stretch of coast begins near the Devil's Thumb at about latitude 74° 30′ and extends, with some interruption, for about 150 miles along the coast of Melville Bay.[28] On the northeast coast the recent explorations of the Danes indicate that there are two stretches of 20 and 60 miles, respectively,

[26] E. von Drygalski, "Grönland-Expedition," Vol. 1, 1897, Map 7.

[27] R. E. Peary, "Journey in North Greenland," *Geogr. Jour.*, Vol. 11, 1898, pp. 213–240.

[28] T. C. Chamberlin, "Glacial Studies in Greenland, III.," *Jour. Geol.*, Vol. 3, 1895, p. 61.

within which the ice in like manner reaches the sea. These occur on Jökull Bay and on the north shore of the North East Foreland (see Fig. 24).[29]

The Ice Face or Front.—Concerning the form of the front of the inland-ice where it lies upon the land, widely different descriptions have been furnished from different districts. It is necessary

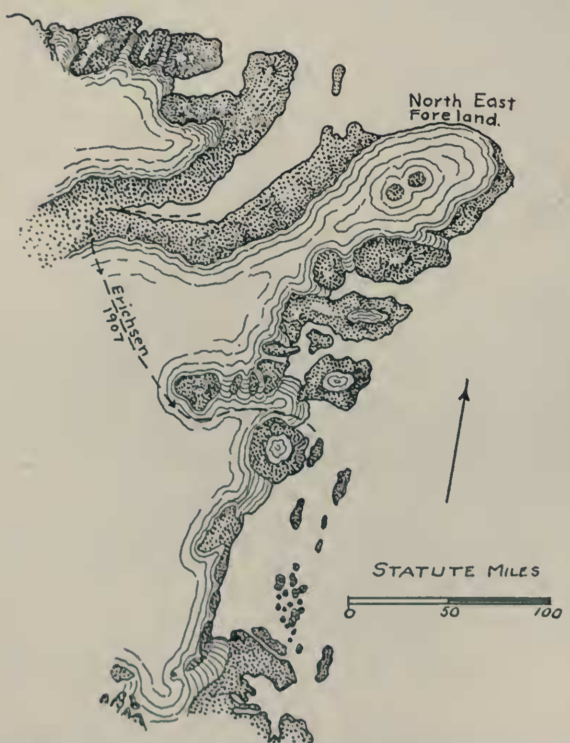

FIG. 24. Map of the Greenland shore in the vicinity of the North East Foreland (after Trolle).

to remember that the continent of Greenland stretches northward through nearly 24° of latitude, and after due regard is had to this consideration, the differences in configuration may perhaps be found to be but expressions of climatic variation. Those who have

[29] Lieut. A. Trolle, "The Danish Northeast Greenland Expedition," *Scot. Geogr. Mag.*, Vol. 25, 1909, pp. 57–70 (map and illustrations).

studied the land margin of the isblink in North Greenland, all call attention to the precipitous and generally vertical wall which forms the ice face (see Plate XXVI, *B*). As a result of shearing and overthrusting movements within the ice near its margin, as well as to the effect of greater melting about the rock fragments imbedded in the lower layers of the ice, the face sometimes even overhangs in a massive ice cornice at the summit of the wall (see Plate XXVII, *A*).[30]

That to this remarkable steepness of the ice face as observed north of Cape York there are exceptions, has been mentioned by both Chamberlin and Salisbury, but Peary has also emphasized the vertical face as a widely characteristic feature of North Greenland. The recent Danish expedition to the northeast coast of Greenland has likewise furnished examples of such vertical walls. An instance where the ice face appears as a beautifully jointed surface somewhat resembling the rectangular joint-walls in the quarry faces of certain compact limestones, is reproduced from the report of the expedition in Plate XXVII, *B*.[31]

Attention has already been called to the precipitous front, the so-called "Chinese Wall," which Lieutenant Lockwood found to form the land face of the inland-ice of Ellesmere Land—a face which was followed up and down over irregularities of the land surface, and whose height in one place was roughly measured as 143 feet (see Fig. 15, p. 75).

From central and southern Greenland, on the other hand, we hear little of such ice cliffs as have been described, and Tarr in studies about the margin of the Cornell extension of the isblink[32] has shown that here the vertical face is the exception.[33] The normal sloping face as there seen is represented in Plate XXVIII, *A*. In following the ice face for fifteen miles, its slopes were here found to be sufficiently moderate to permit of frequent and easy ascent

[30] Chamberlin, *Jour. Geol.*, Vol. 3, 1895, p. 566. Salisbury, *ibid.*, Vol. 4, 1896, p. 778.

[31] Gunnar Andersson, "Danmarks expeditionen till Grönlands nordostkust," *Ymer*, Vol. 28, 1908, pp. 225–239, maps and 7 figures.

[32] To the south of the upper Nugsuak Peninsula in latitude 70° 10′ N.

[33] R. S. Tarr, "The Margin of the Cornell Glacier," *Am. Geologist*, Vol. 20, 1897, pp. 139–156, pls. 6–12.

and descent. Inasmuch as these sloping forms are characteristic of the ice front in the warmer zones, and further correspond to that generally characteristic of mountain glaciers in lower latitudes, it seems likely that its occurrence in Greenland is limited to districts where surface ablation plays a larger rôle.

In northeast Greenland (lat. 77°–82°) according to the Danes, "the frontier of the inland ice is in some places quite steep, in other places you might have mounted the inland ice without knowing it."

Features Within the Marginal Zone.—The larger terraces upon the ice slope, Nansen has ascribed to peculiarities of the rock floor on which the ice rests. Where the slopes become still more accelerated toward the margin of the ice, deep crevasses appear upon these steps running parallel to their extension, and hence parallel to the margins of the ice. Nansen found, however, that such crevasses were restricted to the outer seven or eight miles on the eastern side of his section, and to the outer twenty-five miles on its western margin. Peary in his reconnoissance across the ice border in latitude 69½°, saw such crevasses while they were opening and the surface snow was sinking into the cleft thus formed. The visible opening of the cleft was accompanied by peculiar muffled reports which rumbled away beneath the crust in every direction.[34] Of the terraced slope and its fading into the plateau above he says:

> The surface of the "ice-blink" near the margin is a succession of rounded hummocks, steepest and highest on their landward sides, which are sometimes precipitous. Farther in these hummocks merge into long, flat swells, which in turn decrease in height towards the interior, until at last a flat gently rising plain is revealed which doubtless becomes ultimately level.[35]

In sketching the general form of the Greenland continental glacier, it has been stated that the highest portion of the shield lies to the eastward of the medial line of the continent. This is shown by Nansen's section, and is emphasized by Peary, who says:

> That the crest of the Greenland continental ice divide is east of the country's median line there can be no doubt.[36]

[34] *Jour. Am. Geogr. Soc.*, Vol. 19, 1887, p. 277.
[35] *Geogr. Jour.*, Vol. 11, 1898, pp. 217, 218.
[36] *Geogr. Jour.*, *l. c.*, p. 232.

By von Drygalski[37] this lack of symmetry of the ice material has been ascribed to excessive nourishment upon the east, whereas the losses from melting and from the discharge of bergs occur mainly upon the west. The mountains of the east are, he states, completely surrounded by ice so that peaks alone project, while the mountains of the west stand isolated from the ice. In attempting to make the eccentric position of the boss in the ice shield depend upon the configuration of the underlying rock surface, von Drygalski has been less convincing, for we know that the Scandinavian continental glacier of Pleistocene times moved northwestward from the highest surface of the ice-shield up the grade of the rock floor, and pushed out through portals in the mountain barrier which lies along the common boundary of Sweden and Norway. Still there would appear to be a clear parallel between the marginal terraces of the inland-ice with their crevassed steep surfaces, and the plateaus and ice falls which alternate upon the slopes of every mountain glacier which descends rapidly in its valley.

Superimposed upon the flats of the larger ice terraces, there are undulations of a secondary order of magnitude, and these Nansen ascribed to the drifting of snow by the wind. To the important action of wind in moulding the surface of the inland-ice we shall refer again. There are in addition many other irregularities of the surface due to differential melting, and while of very great interest, their consideration may profitably be deferred until the meteorological conditions of the region have been discussed. There are, however, other features which like the broader terraces are clearly independent of meteorological conditions, and which are, therefore, best considered in this connection.

Dimples or Basins of Exudation Above the Marginal Tongues. —Seen from the sea in Melville Bay on the northwest coast, the inland-ice offers special advantages for observing its contours in sections parallel to its front, that is to say, in front elevation. Here only upon the west coast the ice extends beyond the borders of the land and is cut back by the sea to form cliffs. These ice cliffs are

[37] E. von Drygalski, "Die Eisbewegung, ihre physikalischen Ursachen und ihre geographischen Wirkungen," *Pet. Mitt.*, Vol. 44, 1898, pp. 55–64.

interrupted by rocky promontories which are surrounded on all sides but the front by ice, and hence in reality the cliff furnishes us with sections through nunataks and inland-ice alike. Says Chamberlin:[38]

> Only a few of the promontories of the coast rise high enough to be projected across this sky line and interrupt the otherwise continuous stretch of the glacial horizon. The ice does not meet the sky in a simple straight line. It undulates gently, indicating some notable departure of the upper surface of the ice tract from a plane. As the ice-field slopes down from the interior to the border of the bay, it takes on a still more pronounced undulatory surface. It is not unlike some of our gracefully rolling prairies as they descend from uplands to valleys, when near their middle-life development.

The two 1,200-mile sledge journeys of Peary in the years 1891–92, and 1893–95 across the northern margin of the "Great Ice" of Greenland, have added much to our knowledge of the physiography of the inland-ice. These journeys were made on nearly parallel lines at different distances from the ice border, and so, if studied in relation to each other, they display to advantage the configuration of the ice surface near its margin (see Fig. 25). The routes were for the most part nearly straight and ran at nearly uniform elevations which ranged from 5,000 to 8,000 feet above the sea.[39] In the sections nearest the coast, however, the route at first ascended a gentle rise to a flatly domed crest upon the ice only to descend subsequently into a broad swale of the surface, the bottom of which might be described as a plateau, and which was continued in the direction of the coast by a tongue-like extension of the ice, such as the tongue in Petermann Fjord between Hall Land and Washington Land (Fig. 25). On the further side of this basin-like depression, the surface again rose until another domed crest had been reached, after which a descent began into a swale similar to the first. On the return journey by keeping farther from the ice margin these elongated dimples upon the ice surface were avoided. The broad domed surfaces which separate the dimples clearly lie over the land ridges between the valleys down which the glacier tongues descend toward the sea.

[38] "Glacial Studies in Greenland, III.," *Jour. Geol.*, Vol. 3, 1895, p. 63.

[39] *Geogr. Jour.*, Vol. 11, 1898, p. 215. See also his map, *Bull. Am. Geogr. Soc.*, Vol. 35, 1903, p. 496.

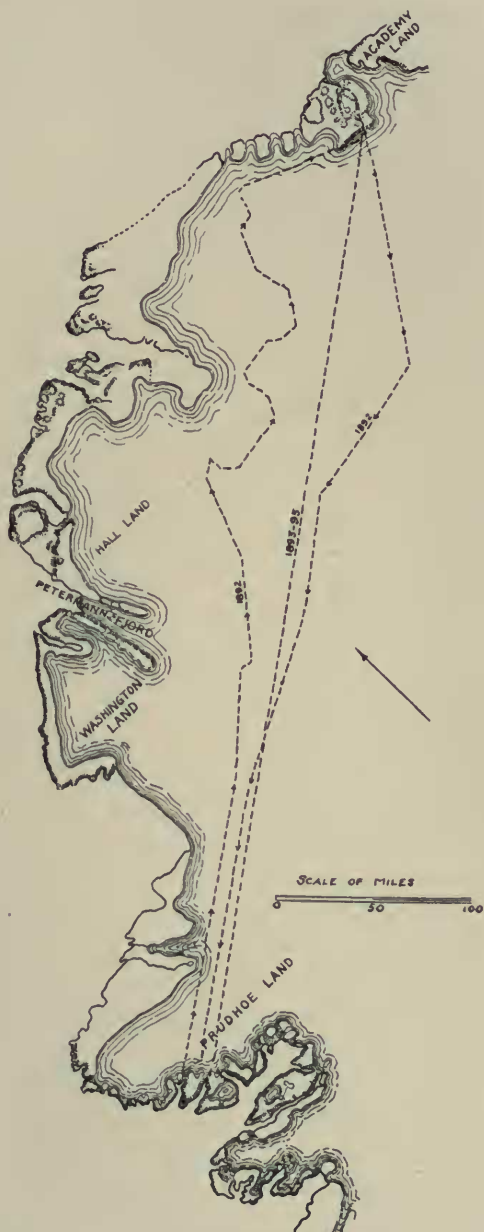

FIG. 25. Map showing routes of sledge journeys in North Greenland in their relation to the margin of the ice (after Peary).

Peary has referred to these dimples on the surface of the inland-ice as "*basins of exudation,*" and has compared the cross profile in its ups and downs to that of a railroad located along the foot-hills of a mountain system.[40] In his earlier reconnaissance of the isblink from near Disco Bay, Peary describes such a dimple above the Jakobshavn ice tongue "stretching eastward into the 'ice-blink,' like a great bay," as a *feeder basin*.[41] The exact form of such dimples upon the ice surface is well brought out in von Drygalski's map of the Asakak glacier tongue on the Umanak Fjord (see Fig. 22, p. 82).[42]

We may easily account for the existence of these dimples by drawing a parallel from the behavior of water as it is being discharged from a lake through a narrow and steeply inclined channel. Under these circumstances the surface is depressed through the indrawing of the water on all sides to supply the demands of the outflowing current. That within the upper portions of the glacier tongues of the Greenland isblink the ice flows with a quite extraordinary velocity has long been known. Values as high as 100 feet per day have been determined upon the Upernavik glacier.[42a] By more accurate methods, von Drygalski has obtained on one of the ice tongues which descends to a fjord, a rate of about 18 meters or 59 feet in twenty-four hours.[43] Upon the inland-ice some distance back from the head of the fjord, on the other hand, a rate was measured of only one to two centimeters per day.

Scape Colks and Surface Moraines.—The velocities of ice movement which obtain within and about the heads of the glacial tongues are, there is thus every reason to believe, as different as possible from the ordinary general outward movement of the inland-ice. Within this marginal zone areas of exceptional velocity of the inland-ice are likely to be found wherever its progress is interfered with by the projecting nunataks. Just as jetties by constricting

[40] *Geogr. Jour.*, Vol. 11, p. 232.

[41] *Jour. Am. Geogr. Soc.*, Vol. 19, 1887, p. 269.

[42] "Grönland-Expedition," *l. c.*, map 7.

[42a] Lieut. C. Ryder in 1886. Helland on a glacier of the Jakobshavnfjord found a rate of 64 feet daily.

[43] E. von Drygalski, "Die Bewegung des antarktischen Inlandeises," *Zeitsch. f. Gletscherk*, Vol. 1, 1906–7, pp. 61–65.

the channels greatly accelerate the velocity of stream flow within those channels, so here within the space between neighboring nunataks a local high rate of flow in the ice is developed. An inevitable and quite important consequence of this constriction was long ago pointed out by Suess and illustrated by the area between Dalager's Nunataks near the southwestern border of the isblink.[44] Here again the conduct of water which is being discharged through narrow outlets has supplied both the illustration and the explanation. In the regulation of the flow of the Danube below Vienna, the river was partially closed by a dam, the Neu-Haufen dyke, and the floor in the channel below the dike was paved with heavy stone

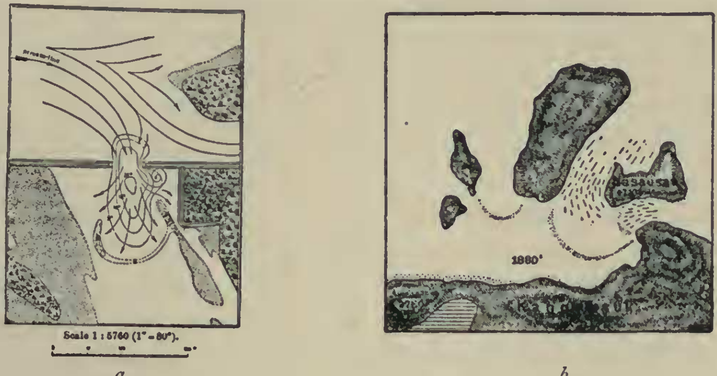

FIG. 26. *a*, Closure of the Neu-Hauen dyke, Schüttau in the regulation of the Danube below Vienna (after Taussig); *b*, scape colks near Dalager's Nunataks (after Jensen and Kornerup).

blocks. The effect of thus narrowing the channel of the river was to raise the level of the water above the dike by almost a meter, and under this increased head the current tore out the heavy stone paving of the floor of the channel and dug a depression above as well as below the outlet. This excavation by the current represented a hole dug to a depth of about fifteen meters. The blocks which had been torn out from the pavement were left in a crescent-shaped border to the depression upon its downstream side (see Fig. 26, *a*).

[44] Ed. Suess, "Face of the Earth," Vol. 2, 1888 (translation, 1906), pp. 342–344.

The position of a surface moraine which stretches in a sweeping arc from the lower edge of one of Dalager's Nunataks to a similar point upon its neighbor, indicates a complete parallel between the motion of the ice and the water at the Neu-Haufen dyke, the rock débris of the deeper ice layers being here brought up to the surface. Study of the Scandinavian inland-ice of late Pleistocene times throws additional light upon the nature of this process. Flowing from a central boss near the head of the Gulf of Bothnia, the ice pushed westward and escaped through narrow portals in the escarpment which now follows the international boundary of Sweden and Norway. This constriction of its current has been appealed to by Suess to account for the interesting glint lakes which to-day lie across this barrier and extend both above and below the former outlets of the ice.[45] Lakes which have this origin he has described under the term scape colks. Perhaps if examined more carefully we should find that the bringing up of the englacial débris to the surface of the ice, is only partially due to the inertia of motion in the ice. With the more rapid flow of the ice within the constricted portion, the basic portions, shod as they are with rock fragments, accomplish excessive abrasion upon the rock bed. This is in accord with Penck's law of adjusted cross sections in glacial erosion. Where the ice channel broadens below the nunataks, the abrasion again becomes normal so that a wall develops at this place in the course of the stream.

Here, therefore, a new process comes into play due to the peculiar properties of the plastic ice, a process which has been illustrated in the formation of drumlins beneath former continental glaciers, and has been given an experimental verification. Case has shown that paraffin mixed with proper proportions of refined petroleum, and maintained at suitable temperatures, can be forced by means of plungers[46] through narrow boxes open at both ends. It was shown in the experiments that an obstruction interposed at the bottom and in the path of the moving paraffin, forced the bottom layers upward, and this upward movement continued beyond

[45] Suess, *l. c.*, pp. 337–346.

[46] E. C. Case, "Experiments in Ice Motion," *Jour. Geol.*, Vol. 3, 1895, pp. 918–934.

the position of the obstruction. The experiments of Hess[47] give results which are consistent with those of Case. Hess employed in his experiments parallel wax disks of alternating red and white colors, and these were forced under hydraulic pressure through a small opening. It was found that the layers turn up to the surface in this "model glacier" apparently as a result of the friction upon the bottom and at only moderate distances from the opening where the energy of the active moving substance pressing from the rear has to some extent been dissipated.

In Chamberlin's studies of certain Greenland glaciers, he was permitted to observe the effect upon the motion of the glacier of low prominences in its bed. These observations are confirmatory of the experiments described.[48]

The swirl colks or eddies which Suess has suggested as occurring below nunataks, in order to account for certain lakes in Norway, seemed to be much less clear, and it is a little difficult to assume an eddy in the ice which is in any way comparable to the eddies of water.

Marginal Moraines.—Inasmuch as the rock appears above the surface of the ice of the Greenland continental glacier only in the vicinity of its margins, and here only as small islands or nunataks, the rock débris carried by the Greenland ice must be derived almost solely from its basement. As described in detail by Chamberlin, it is the lower 100 feet of ice to which englacial débris is largely restricted.[49] Medial moraines, if the term may be properly applied to those ridges of rock débris which upon the surface of the ice go out from the lower angles of nunataks, have been frequently described by Nansen and others. They seem to differ but little from certain of the medial moraines which have been described in connection with the larger mountain glaciers.

Nansen has mentioned heavy terminal moraines in the Austmann Valley where he came down from the inland-ice after crossing the

[47] "Die Gletscher," 1904, p. 171, fig. 28.

[48] "Recent Glacial Studies in Greenland." Annual address of the President of the Geological Society of America, *Bull. Geol. Soc. Am.*, Vol. 6, 1895, pp. 199–220, pls. 3–10.

[49] Chamberlin, *l. c.*, p. 205.

continent. The material of these moraines consisted mainly of rounded and polished rock fragments, and is obviously englacial material.[50] Along the land margin of the Cornell ice tongue Tarr found a nearly continuous morainic ridge parallel to the ice front. This ridge usually rests at the base of the ice foot, and is sometimes a part of this foot, wherever débris has accumulated and protected the ice beneath from the warmth of the sun. Such an accumulation causes this part of the glacier to rise as a ridge. In other cases the ridge is, however, separated from the ice margin, and sometimes there are several parallel ridges from which the ice front has successively withdrawn[51] (see Plate XXVIII, *B*).

According to von Drygalski the marginal moraines of the Greenland ice sheet as regards their occurrence, form, and composition, are in every way like those remaining in northern Europe from the time of the Pleistocene glaciation, and this is true of those which run along the present border of the inland-ice as well as of those still mightier ancient moraines which follow at certain distances.[52] These moraines are generally closely packed blocks with relatively slight admixture of finer material. They are the largest where the ice border enters the plains, or pushes out upon a gentle slope, and they are smallest where the ice passes steep rocky angles.

It is worthy of note that the marginal moraines of Greenland become locally so compact and resistant that they oppose a firm obstruction to the ice movement. Then the ice pushes out laterally into the marginal lakes which develop there or pushes up upon the moraines. It thus comes to arrange its layers parallel to the slope of the morainic surface or, in other words, so that they dip toward the ice.[53]

Another type of marginal moraine which was mentioned by Mohn and Nansen from south Greenland, and later fully described by Chamberlin from north Greenland, is explained by the upturn-

[50] Mohn u. Nansen, "Wissenschaftlicheir Ergebnisse von Dr. F. Nansen's Durchquerung von Grönland, 1888," *Pet. Mitt. Ergänzungsb.*, 105, 1892, p. 91.

[51] R. S. Tarr, "The Margin of the Cornell Glacier," *Am. Geol.*, Vol. 20, 1897, p. 148.

[52] Grönland-Expedition, *l. c.*

[53] von Drygalski, *l. c.*, p. 529.

ing effect of obstructions in the bed, and by the shearing and overthrusting movements which are found to exist in inland-ice near its margin[54] (see Figs. 27 and 28). This process has much in

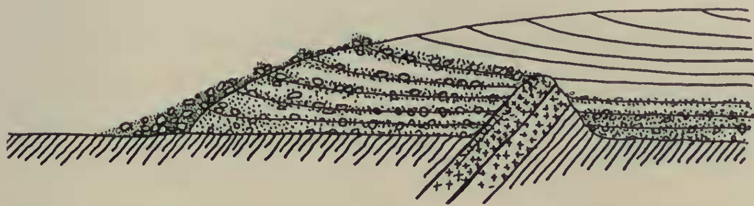

FIG. 27. Diagram to show the effect of a basal obstruction in the path of the ice near its margin (after Chamberlin).

common with that which we have already described in connection with scape colks.

Fluvio-glacial Deposits.—Where studied by Chamberlin near Inglefield Gulf, there appears to be little or no gushing of water from beneath the inland-ice. Small streamlets only appeared be-

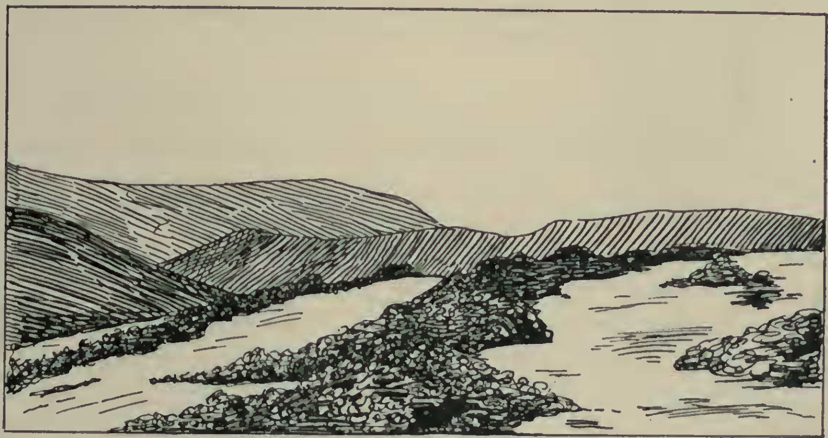

FIG. 28. Surface marginal moraine of the inland ice of Greenland.

neath the ice border, bringing gravel and sand which they distributed among the coarser morainic material. So far as land has been recently uncovered by the ice in north Greenland, and so far as differentiated from the topography of the underlying rock, it was

[54] Chamberlin, *l. c.*, p. 92.

found to be nearly plane. So far as known, no eskers have been observed about the border of the inland-ice of Greenland and only a few irregular kames near Olrik's Bay.[55]

Nourishment of the Greenland Inland-ice.

Few and Inexact Data.—The problems involving the gains and the losses of the inland-ice of Greenland require for their satisfactory solution a much larger body of exact data than we now possess. Barring a few scattered and not always exact or reliable observations, we are practically without knowledge of the amount or the variations of atmospheric pressure, or of snowfall away from the coastal areas of the continent. Even within these marginal zones, the losses from ablation and through the calving of bergs have been estimated by crude methods only. Again, the great height of the ice surface within the central plateau, and the lack of any knowledge of the elevation of the land surface in those regions, has raised questions concerning the conditions of flow and of fusion upon the bottom, which will probably long remain subjects of controversy.

An international coöperative undertaking with one or more stations established in the interior at points where altitude has been determined by other than barometric methods, and with coast stations maintained contemporaneously and for a period of at least a year, particularly if they could be supplemented by balloon or kite observations, would yield results of the very greatest importance.[56] The Greenland ice having shrunk greatly since the Pleistocene period, it is almost certain that its alimentation to-day does not equal the losses which it suffers along its margins—which in but slightly altered form applies to the Antarctic continental glacier as well.

Snowfall in the Interior of Greenland.—Almost the only data upon this subject are derived from a rough section of the surface layers of snow, as this was determined by Nansen with the use of

[55] Salisbury, *l. c.*, p. 809.

[56] Robert Stein, "Suggestion of a Scientific Expedition to the center of Greenland," Congrés Intern. pour l'Étude des Regions Polaires, Brussels, 1906, pp. 1–4 (separate).

a staff near the highest point in his journey across the inland-ice along the 64th parallel. At elevations in excess of 2,270 meters Nansen found the surface snow "soft" and freshly fallen, but of dust-like fineness. Beneath the surface layer, a few inches in thickness only, there was a crust less than an inch in thickness which was ascribed to the slight melting of the surface in midsummer,[56a] and below this crust other layers of the fine "frost snow" more and more compact in the lower portions, but reaching a thickness of fifteen inches or thereabouts before another crust and layer was encountered.[57] Other sections made in like manner by pushing down a staff, revealed similar stratification of the surface snow with individual layers never exceeding in thickness a few feet. From these observations Nansen has drawn the conclusion that the layers of his sections correspond to seasonal snowfalls, the thin crust upon the surface of each being due to surface melting in the few warm days of midsummer. He cites Nordenskiöld as believing that the moist winds which reach the continent of Greenland deposit most of their moisture near the margin.[58]

The sky during almost the entire time of the journey is described by Nansen as so very clear that the sun could be seen, and there were few days in which the sky was completely overcast. Even when snow was falling, which often happened, the falling snow was not thick enough to prevent the sun showing through. This clearly indicates that the snow falls from layers of air very near the snow surface below. The particles which fell were always fine, like frozen mist—what in certain parts of Norway is known as "frost snow"; that is, snow which falls without the moisture first passing through the cloud stage.[59]

The air temperatures even in August and September, when the crossing was made, were on the highest levels seldom much above the zero of the Fahrenheit scale, and at night they sank by over 40° F. (in one case to — 50° F.).

[56a] In the light of later studies this may as satisfactorily be explained through hardening by the wind.

[57] Mohn u. Nansen, *l. c.*, p. 86.

[58] Nansen, *l. c.*, Vol. 1, p. 495.

[59] Nansen, *l. c.*, Vol. 2, p. 56.

Peary, while on the inland-ice in north Greenland in the month of March, 1894, registered on his thermograph a temperature of — 66° F. and several of his dogs were frozen as they slept.[60] The high altitudes and the general absence of thick clouds over the inland-ice, permit rapid radiation, so that cold snow wastes and hot sand deserts have in common the property of wide diurnal ranges of temperature. The poverty of the air over the inland-ice in its content of carbon dioxide, as shown by the analysis of samples collected by Nansen, must greatly facilitate this daily temperature change.[61]

From studies in the Antarctic it is now known that most of the snow falls there in the summer season, and that little, if any, moisture can reach the interior from surface winds. The same is probably true also of the interior of Greenland.

Though the absolute humidity of the air upon the ice plateau of Greenland is always low, the relative humidity is large, and never below 73 per cent. of saturation in the levels above 1,000 meters. Evaporation occurs chiefly when the sun is relatively high, and when the air is again chilled the abstracted moisture is returned to the surface in the form of the almost daily snow mists or frost snow. The observations went to show that only in the warmest days of summer do the sun's rays succeed in melting a very thin surface layer of the snow. Of the thirty days that Nansen's party was at altitudes in excess of 1,000 meters, on only six is a definite snowfall reported. Within the interior of Greenland it appears that *no snow whatever is permanently lost from the surface by melting*.[62]

While the relative humidity of the air over the central plateau is so high, the absolute humidity is extremely low, being measured from 1.4 mm. to 4 mm., though generally much below the maximum value. The average absolute humidity was 2.5 mm. while the average relative humidity was 92 per cent.[63]

It has been claimed by v. Drygalski that the eastern portion of

[60] *Geogr. Jour.*, Vol. 11, 1898, p. 228.

[61] Mohn u. Nansen, *l. c.*, pp. 109–111.

[62] Nansen, *l. c.*, Vol. 2, p. 491. See also Peary, *Geogr. Journ.*, *l. c.*, p. 214.

[63] Mohn u. Nansen, *l. c.*, pp. 44–45.

the Greenland ice sheet is a great nourishing region, while the western slope, on the other hand, is the locus of excessive melting and discharge. In support of this view he adduces chiefly the admitted lack of symmetry of the ice mass.[64] So far as alimentation is concerned, the view does not seem to be as yet supported by any observations, and it can hardly be regarded as a tenable hypothesis.

The Circulation of Air over the Isblink.—No exact data upon atmospheric pressures are as yet available except from stations near the sea level, mainly along the western and northern coasts. Until stations have been maintained for a more or less protracted period within the interior of Greenland, none can be expected. None the less, upon the basis of the observed winds in those portions of Greenland which have been traversed, it may be safely asserted that a fixed area of high atmospheric pressure is centered over the Greenland isblink, and that the cold surface of this mass of ice is directly responsible for its location there. Nansen, as early as 1890, announced this fact, having observed "that the winds which prevail on the coasts have an especial tendency to blow outwards at all points."[65] After many years of experience in different portions of Greenland, Peary stated the law of air circulation above the continent in clear and forceful language:[66]

> Except during atmospheric disturbances of exceptional magnitude, which cause storms to sweep across the country against all ordinary rules, the direction of the wind of the "Great Ice" of Greenland is invariably radial from the center outward, normal to the nearest part of the coast-land ribbon. So steady is this wind and so closely does it adhere to this normal course, that I can liken it only to the flow of a sheet of water descending the slopes from the central interior to the coast. The direction of the nearest land is always easily determinable in this way. The neighborhood of great fjords is always indicated by a change in the wind's direction; and the crossing of a divide, by an area of calm or variable winds, followed by winds in the opposite direction, independent of any indications of the barometer.

Except for light sea breezes blowing on to the land in February,

[64] E. v. Drygalski, "Die Eisbewegung, ihre physikalischen Ursachen und ihre geographischen Wirkungen," *Pet. Mitt.*, Vol. 44, 1898, pp. 55–64. See also by the same author, "Grönland-Expedition, etc.," pp. 533–539.

[65] Nansen, *l. c.*, Vol. 2, p. 496. Also Mohn and Nansen, *l. c.*, pp. 44–47.

[66] "Journeys in North Greenland," *Geogr. Jour.*, Vol. 11, 1898, pp. 233–234. See also "Northward over the 'Great Ice,'" Vol. 1, pp. lxix–lxx.

the Danish northeast Greenland expedition found "the wind was constantly from the northwest, this being the result of the high pressure of air which is found over the inland ice."[67]

These conditions of circulation are schematically represented in Fig. 29. In March, 1894, Peary encountered on the north slope

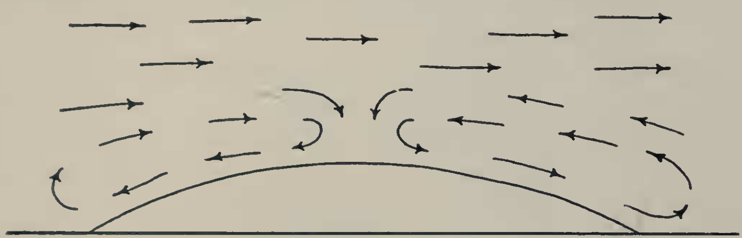

Fig. 29. Diagram to illustrate the air circulation over the isblink of Greenland.

of the inland-ice a series of blizzards before unprecedented in Arctic work, one lasting for three days, during which for a period of 34 hours the average wind velocity, as recorded by anemometer, was 48 miles per hour. Viewed in the light of violent southerly blizzards which Shackelton found to prevail upon the ice plateau in the Antarctic, these winds must be considered as belonging to the same Greenland or isblink system which has been described as of such general prevalence.

After comparing the meteorological data from his journey with contemporaneous observations on the shores of Baffin's Bay, Nansen believed that he was able to make out faintly the influence of general cyclonic movements. He says.[68]

> The plateau seems to be too high and the air too cold to allow depressions or storm centres to pass across, though, nevertheless, our observations show that in several instances the depressions of Baffin's Bay, Davis' Strait and Denmark Strait can make themselves felt in the interior.

Commenting upon Peary's conclusions above quoted, Chamberlin[69] ascribes the wind which flows downward and outward from

[67] Lieut. A. Trolle, R. D. N., "The Danish Northeast Greenland Expedition," *Scot. Geogr. Mag.*, Vol. 25, 1909, pp. 57–70 (map and illustrations).

[68] Nansen, *l. c.*, Vol. 2, p. 496.

[69] *Jour. Geol.*, Vol. 3, 1895, pp. 578–579.

the isblink to a notable increase of its specific gravity through contact with and consequent cooling by the snow surface.[70]

Foehn Winds Within the Coastal Belt.—The sliding down of masses of heavy air upon the snow surface of the Greenland ice must bring about adiabatic heating of the air and a consequent elevation of the dew point. The increase of temperature being about 1° C. for every 100 meters of descent, a rise of temperature of as much as 20° C. or 36° F. will result in a descent from the summit of the plateau, assuming this to have an elevation of 10,000 feet. Some reduction in the amount of this change of temperature will, of course, result from the contact of the air with the cold snow surface during its descent, this modification being obviously dependent upon the velocity of the current. The warm, dry winds which in different districts have been described under the names *foehn* and *chinook* are the inevitable consequence of such conditions, and are, moreover particularly characteristic of steep mountain slopes more or less covered by glaciers. Such foehn winds have long been recognized as especially characteristic of western Greenland. Dr. Henry Rink, who was a pioneer in the scientific study of Greenland, wrote in 1877:[71]

> Among the *prevailing winds* in Greenland the *warm land wind* is the most remarkable. Its direction varies according to locality from true E.S.E. to E.N.E. always proceeding though warm from the ice-covered interior, and generally following the direction of the fjord. It blows as frequently and as violently in the north as in the south, but more especially at the fjord heads, while at the same time in certain localities it is scarcely perceptible. It often turns into a sudden gale; the squalls in some fjords rushing down between the high rocks, in certain spots often sweep the surface of the water with the force of a hurricane, raising columns of fog, while the surrounding surface of the sea remains smooth.

[70] Professor v. Drygalski has shown that in the Great Karajak glacier near the coast in central western Greenland, the temperature of the snow and ice down to a depth of 60 feet or more undergoes a fall of temperature in response to the severity of the winter's cold, but in time this fall in temperature lags behind the period of maximum cold. Below that depth, however, it approximates in temperature to the zero of the centigrade scale. Temperatures of the snow measured just below the surface, varied from —11° to —26° C. (E. von Drygalski, "Grönland-Expedition der Gesellschaft für Erdkunde zu Berlin," 1891–1893, Vol. 1, 1897, pp. 470–472.)

[71] Henry Rink, "Danish Greenland, Its People and Its Products," London, 1877, p. 468.

Nansen encountered one of these foehn winds on his descent, and Peary mentions their occurrence in the north. In Scoresby's Land on the east coast, a foehn wind in the winter season has been known in a single hour to change the temperature by 24° C. (or 43° F.), and the maximum change during such a wind is far greater. It would not appear from observations that the winds of the Greenland system extend to any great distance above the surface, where the broad cyclonic areas in the atmosphere may be presumed to continue their courses with but slight modification. The anti-cyclone of the continent is, however, none the less clear and constant and is centered over the high interior. Nansen has remarked the calms over the divide of his section.[72]

There is some evidence that in adopting the important modern laws of adiabatic cooling of the air, we have allowed the pendulum to swing too far and have given too little weight to the effect of cooling through contact of air with either rock or snow. The latest results of Antarctic expeditions furnish the most striking proof of this, if other than Greenland examples were needed, and the Antarctic studies throw much light upon the conditions of snow distribution which are observed in Greenland.

Wind Transportation of Snow Over the Desert of Inland-ice.—Whymper and Nordenskiöld called Greenland a "Northern Sahara." In different ways Nansen and Peary have each instituted comparisons between the wastes of snow in the interior of Greenland and the desert of sand of the Sahara. The Norwegian explorer has emphasized especially the wide daily ranges of temperature, which because of generally cloudless atmospheres, both deserts have in common. Of the monotonous and elemental simplicity of the snow vistas back from the ice margin in North Greenland, Peary says:[73]

> It is an Arctic Sahara, in comparison with which the African Sahara is insignificant. For on this frozen Sahara of inner Greenland occurs no form of life, animal or vegetable; no fragment of rock, no grain of sand is visible. The traveller across its frozen wastes, travelling as I have week after week, sees outside himself and his own party but three things in all the world, namely, the infinite expanse of the frozen plain, the infinite dome of the cold blue sky, and the cold white sun—nothing but these (see Fig. 30).

[72] Nansen, *l. c.*, Vol. 2, pp. 487–488, 496.

[73] *Geogr. Journ.*, *l. c.*, pp. 214, 215.

There is, however, yet another marked parallel between the snow waste and the sand desert. It is the importance of wind as a transporting agent. In his shorter acquaintance with southern Greenland Nansen was less impressed with this, but he has explained the secondary snow ridges upon the marginal terraces of the inland-ice as wind accumulations.[74] These long parallel ranges of snow drift thus correspond to the similar ranges of sand dunes

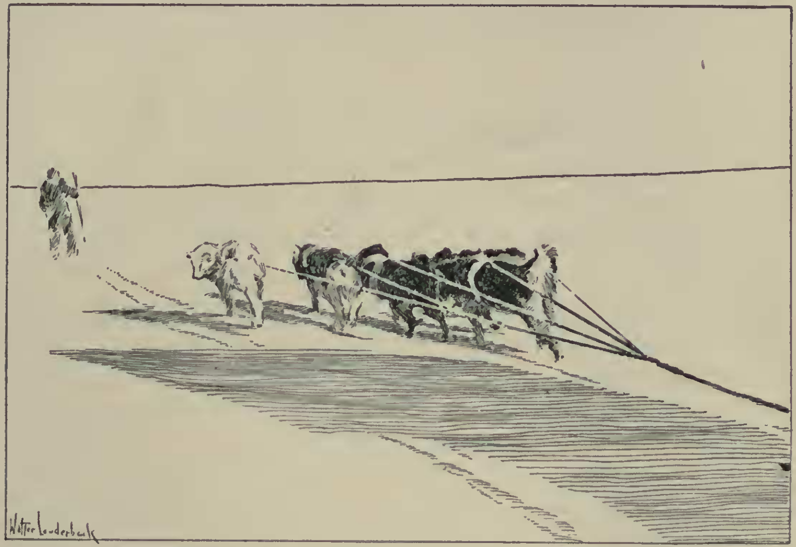

FIG. 30. On the Sahara of Snow (after Peary).

which sometimes throughout a width of many miles hem in the deserts of lower latitudes. In northern Greenland Peary's observations have a special value. He says:[75]

There is one thing of especial interest to the glacialist—the transportation of snow on the ice-cap by the wind. . . .

The opinion has been forced upon me that the wind, with its transporting effect upon the loose snow of the ice-cap, must be counted as one of the most potent factors in preventing the increase in height of the ice-cap—a factor equal perhaps to the combined effects of evaporation, littoral and subglacial melting, and glacial discharge. I have walked for days in an incessant sibilant drift of flying snow, rising to the height of the knees,

[74] Mohn u. Nansen, *l. c.*, p. 78.

[75] *Geogr. Jour.*, *l. c.*, pp. 233–234.

sometimes to the height of the head. If the wind becomes a gale, the air will be thick with the blinding drift to the height of 100 feet or more. I have seen in the autumn storms in this region round an amphitheatre of some 15 miles, snow pouring down in a way that reminds one of Niagara. When it is remembered that this flow of the atmosphere from the cold heights of the interior ice-cap to the lower land of the coast is going on throughout the year with greater or less intensity, and that a fine sheet of snow is being thus carried beyond the ice-cap, to the ice-free land at every foot of the periphery of the ice-cap, it will perhaps be seen that the above assumption is not excessive. I feel confident that an investigation of the actual amount of this transfer of snow by the wind is well worth the attention of all glacialists.

Fringing Glaciers Formed from Wind Drift.—In the vicinity of Inglefield Gulf in northwest Greenland, the inland-ice ends in a steep, snowy slope rising to a height of about 100 feet, where is a terminal moraine, above which moraine rises the great dome of the inland-ice. The whiteness and freshness of a portion of the snow of the outer border, when examined by Chamberlin,[76] showed it to be wind drift of recent accumulation. Locally, however, older and discolored snow appeared beneath the whiter surface snow, and in a few places stratified granular ice with some included rock débris. This snow and ice becomes augmented from year to year and is, in Chamberlin's opinion, a species of *fringing glacier*. Such fringes were from a few rods to a half mile in breadth, and where a favorable depression existed, one was observed extending for a mile or more down the valley. Commander Peary has found this a dominant feature on the north Greenland coast. Fringing glaciers of this type have also been described by Salisbury from the vicinity of Melville Bay. Their movement was clearly evinced by their structure and by the débris which they carried.[76a]

Nature of the Surface Snow of the Inland-ice.—The surface snow from the marginal zones of the inland-ice has the granular form characteristic of névés, as has been shown with exceptional clearness in elaborate studies by von Drygalski.[77] Such grains, grown by accretions from a single crystal nucleus and at the ex-

[76] T. C. Chamberlin, "Glacial Studies in Greenland, VI.," *Jour. Geol.*, Vol. 3, 1895, pp. 580–581.

[76a] Salisbury, *Jour. Geol.*, Vol. 3, p. 886.

[77] "Grönland-Expedition," etc., Vol. 1, 1897.

pense of neighboring crystals, must require either fusion from temporary elevation of temperature, or from pressure. The observations of von Drygalski were made on the ice of the marginal tongues and on the blue layers of the inland-ice; but as the samples taken farthest from the margins were found at a height of only 500 meters, the results throw little light upon the conditions of surface snow within the interior, where melting does not take place. In view of recent studies in Antarctica it is unlikely that firn or névé snow will be found within the interior except at considerable depths below the surface.

Nansen has described the fine "frost snow" which falls almost daily from an air layer near the snow surface, from which its moisture has been derived. Melting does not occur there, as already stated, except perhaps for a few days in the height of summer when a thin crust develops upon the surface.[78] Peary has referred to the snow at the highest altitudes which he reached in north Greenland as "unchanging and incoherent." This dry hard snow chased by the wind, has the cutting effect of sand in a blast, and thus is offered still another parallel with deserts and their wind blown sand. Each new storm, we are told by Stein,[79] piles up a snowbank on the lee sides of nunataks, but the next storm, coming from a somewhat different direction and laden with fine hard snow, cuts away the earlier deposit as would a sand blast. Peary discovered one of his earlier snow huts partly cut away by this process.

Snow Drift Forms of Deposition and Erosion—sastrugi.—The minor inequalities of the snow surface as determined by the wind blowing over the inland-ice, have been mentioned more or less persistently by all Arctic travellers, since upon the character of this surface has so largely depended the celerity of movement in sledge journeys. It is unfortunate that no one has discussed the subject from a scientific standpoint, for it has great significance in connec-

[78] "Thus it will be seen that at no great distance from the east coast the surface of dry snow begins, on which the sun has no other effect than to form a thin crust of ice. The whole of the surface of the interior is entirely the same." (Nansen, *l. c.*, Vol. 2, p. 478.)

[79] Robt. Stein, Congrés international pour l'étude des regions polaires. Brussels, 1906, pp. 1–4 (separate).

tion with the study of the strength and direction of the wind over the snow surface. All minor hummocks and ridges of this nature are included under the general term *sastrugi* (see Fig. 31).

The student may learn much concerning their form within the Antarctic regions from examination of the many beautiful photographs recently published by the Royal Society in connection with

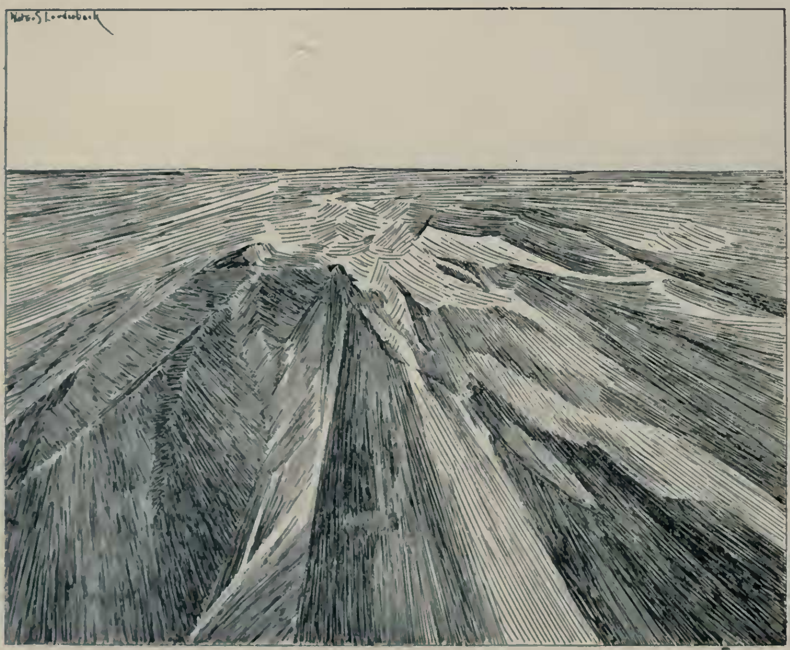

FIG. 31. Sastrugi on the inland-ice of North Greenland (after Peary).

the British Antarctic Expedition.[80] On Plate 92 of this collection, sastrugi are shown which were originally laid down in "elongated domes" and "crescent hollows," but which on account of change in the wind direction the drifting snow granules have cut away both on the soft surface and in the harder deep layers. As a result of this erosion cross flutings have been superimposed upon the original forms.

[80] National Antarctic Expedition, 1901–4. Album of photographs and sketches (with brief descriptions, Ed.), London, 1908.

Our best study of snow drift forms has been made by Dr. Vaughan Cornish, who, after a series of monographs dealing with waves of drifted sand, has spent a winter in Canada in order to study the phenomena connected with the drifting of snow.[81] It is found that snow which falls at temperatures near 32° F. is wet and sticky, and behaves quite differently from that which falls near or below the zero of the same scale; which, on the contrary, is dry and slippery. Subsequent modifications of either of these forms of snow depend chiefly upon pressure, temperature, radiation and wind. It is the cold, dry and granular snow only which makes so-called *normal* waves, and it must be this form which plays the major rôle in producing the surface irregularities of the inland-ice of Greenland.

Ripples and larger waves alike, when formed from granular snow and when shaped by wind accumulation, *have the steep side always to leeward,* in which respect the snow behaves like drifted sand. In order to produce waves or ripples the wind must have a velocity sufficient to be thrown into undulations by the irregularities of the surface over which it blows. The most perfectly moulded forms are naturally produced upon a relatively plane surface, such as is realized on the inland-ice of Greenland—the "imperial highway" of Commander Peary.

Apparently the direction of the greatest extension of the sastrugi will depend upon the strength of the wind and upon the amount of snow which is being transported, much as has been found to be the case with drifted sand.[82] Thus, with small amounts of snow and moderate winds, the characteristic form of sastrugi is a short, scalloped ridge lying across the wind direction and in form not unlike an ox-yoke—something intermediate between a barchan and a transverse ridge. Barchans of snow almost identical in form with sand barchans, are produced apparently under like conditions, the chief differences being that lighter winds suffice

[81] Vaughan Cornish, "On Snow-waves and Snow-drifts in Canada," *Geogr. Jour.*, Vol. 20, 1902, pp. 137–175.

[82] P. N. Tschirwinsky, "Schneedunen und Schneebarchane in ihrer Beziehungen zu äolischen Schneeablagerungen im Allgemeinen," *Zeitsch. f. Gletscherk.*, Vol. 2, 1907, pp. 103–112.

to accomplish the result with the less ponderous snow, and that the resulting forms set quicker in the snow (see Fig. 32, *a*).

Cornish has realized the full importance of snow-blast erosion in modifying the form of snow drifts. His *barchans of erosion,* in plan resemble the barchans of deposition from which they are derived, but unlike the depositional forms their broader surface is concave upward instead of convex, and their steeper face is toward the wind (see Fig. 32, *b*).

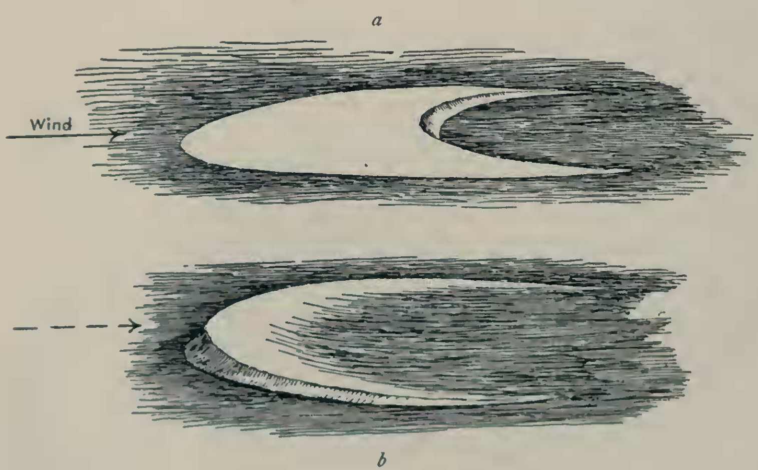

Fig. 32. Barchans in snow. *a*, of deposition; *b*, of erosion (after Cornish).

Some facts of importance which concern the density of the snow are emphasized by Cornish, and apply with especial force to the surface snow of inland-ice. It was found that crusts upon the surface of snow do not necessarily imply melting, but are produced in temperatures below the fusion point. When the air temperatures at Winnipeg ranged from 25° to —28° F. the snow surface over the river set so hard that the mocassined heel did not dent it. Pieces of this snow broken off and held up to the sunlight showed a "mosaic of small translucent icy blocks cemented firmly by opaque ice." The effect upon snow density of the radiation from the surface and of pressure from the wind, were strikingly brought out by a number of observations. Newly fallen snow in Canada has a density of about 0.1. Over the level surface about Winnipeg in the month of January and at a temperature of 10° F., the snow was found to have a density within the upper two feet of 0.38; while in the woods at the same time and at the same depth, here without a crust, its density was 0.19. Thus it is seen that the snow in the woods is about twice as heavy as newly fallen snow, but only about half as heavy as that which has been chased about by the wind. At Glacier House in the Selkirks, where the snow is shielded from the wind within a narrow valley, experiments showed a density of 0.106 at the surface, whereas at a depth of one foot below the surface the density was 0.195, and at a depth of four feet, 0.354. The middle value being that of the snow in the woods at Winnipeg, it is seen that the weight of an additional three feet of snow is necessary in order to pack snow as tightly as is done by the wind blowing over the prairie. After a time, as a result of this treatment by the wind, an eight-inch snowfall dwindles by packing in the woods to four inches, and over the open plain to a two-inch layer.

In eroding a drift, the wind first attacks the softer surface layer. This removed, the snow of the blast adheres less to the surface of the drift, and in consequence abrades it more vigorously. Thus, notches in the ridges, instead of being mended by the detritus, are increased by it, and transverse ridges are presently cut through, and we pass by stages from an arrangement of ridges transverse to the wind to that of longitudinal structures having the greatest extension parallel to the wind.[83] These longitudinal sastrugi appear to be the dominant ones, and from them the direction of prevailing winds may be determined as has been already proven in the Antarctic. On the Siberian tundras the sastrugi are often the only guides of direction which the natives have.[84]

Source of the Snow in Cirrus Clouds.—What has been learned of the circulation of air above the continental ice of Greenland makes it extremely unlikely that any such excessive alimentation upon the eastern margin through ordinary snow fall, as has been

[83] Cornish, *l. c.*, pp. 159–160.

[84] Tschirwinsky, *l. c.*, p. 107.

advocated by von Drygalski, can occur.[85] Such moisture-laden air as can, under normal conditions, reach the interior plateau must descend from higher levels in the anti-cyclone above the central boss, and be distributed by the outward flowing surface currents. From such altitudes the moisture would probably be congealed in the form of fine ice needles, such as are believed to exist in cirrus clouds. The snow which covers the surface at these levels appears, moreover, to have this character. Of greatest interest in this connection is the observation of Nansen that while the sky was, during the time of his crossing, in the main clear, those clouds which were present were generally either cirrus clouds or some combination of cirrus with cumulus and stratus clouds. No cumulus clouds whatever were observed. In tabular form his results are as follows:

Form of Clouds.	No. of Days.		Per Cent.
Cirrus	23	51	44
Cirro-stratus	17		33
Cirro-cumulus	11		21
Cumulo-stratus	22		42
Stratus	10		19

As already stated, such snow as reaches the central area must, it would seem, be derived from the cirrus clouds which at higher levels move in toward the anti-cyclone and descend as surface currents over the "Great Ice."

Depletion of the Greenland Ice from Surface Melting.

Eastern and Western Slopes Compared.—Though it is probably not true, as has been claimed by von Drygalski, that the eastern border of the continent is the locus of nourishment for the ice, it is almost certain that the losses are much greater along the western margins. For this there are several reasons. In the first place, the eastern base is apparently characterized by lower temperatures. The cold ocean current, which carries ice bergs and flows from the

[85] "The east is to be regarded as the region of origin of snow, the west as the terminal region of the Greenlandic glaciation." (E. von Drygalski, "Die Eisbewegung, ihre physikalischen Ursachen und ihre geographischen Wirkungen," *Pet. Mitt.*, Vol. 44, 1898, pp. 55–64.)

Arctic Ocean southward in Baffin's Bay, follows the western shore, while a warmer counter current flows northward along the eastern or Greenland coast at least in its southern stretches. Tarr thinks this current may reach as far as Melville Bay.[86] In addition, the gentler slopes of the western surface of the ice are perhaps more favorable to the warm and dry "thaw wind"—the well-known foehn of Greenland.

Again, ablation or surface melting is to a large extent dependent upon the quantity of rock débris which is blown onto the ice surface from its margins. In southern Greenland, at least, the wider ribbon of exposed shore land upon the western coast conspires with the prevailing western winds to make a more effective marginal attack upon the anti-cyclone of the continent. Nansen reports that he found on the east coast none of the rock dust first described by Nordenskiöld as "cryoconite," though it extended inward from the western coast as much as 30 kilometers.[87]

Still further it is to be remembered that the ice of the west margin is intersected by many deep fjords, which communicating with the open sea, remove an enormous quantity of ice in the form of bergs. Upon the eastern coast the pack-ice prevents the removal of bergs except from the southern latitudes.

Effect of the Warm Season Within the Marginal Zones of the Inland-ice.—In winter the entire surface of the ice and the border of the land as well, are covered with an unbroken layer of fine, dry snow. The suddenness of the change to summer within the land zone outside the ice front, has been emphasized by Trolle. The temperature of the snow upon the land in northeast Greenland rose gradually with the arrival of summer until the melting point was reached, and then in one day all the snow melted. "The rivers were rushing along, flowers were budding forth, and in the air the butterflies were fluttering." [88]

The snow upon the surface of the inland-ice where studied by

[86] R. S. Tarr, "Difference in the Climate of the Greenland and American Sides of Davis' and Baffin's Bay," *Am. Jour. Sci.*, Vol. 3, 1897, pp. 315–320.

[87] Mohn und Nansen, *l. c.*, p. 90.

[88] Trolle, *l. c.*, p. 66.

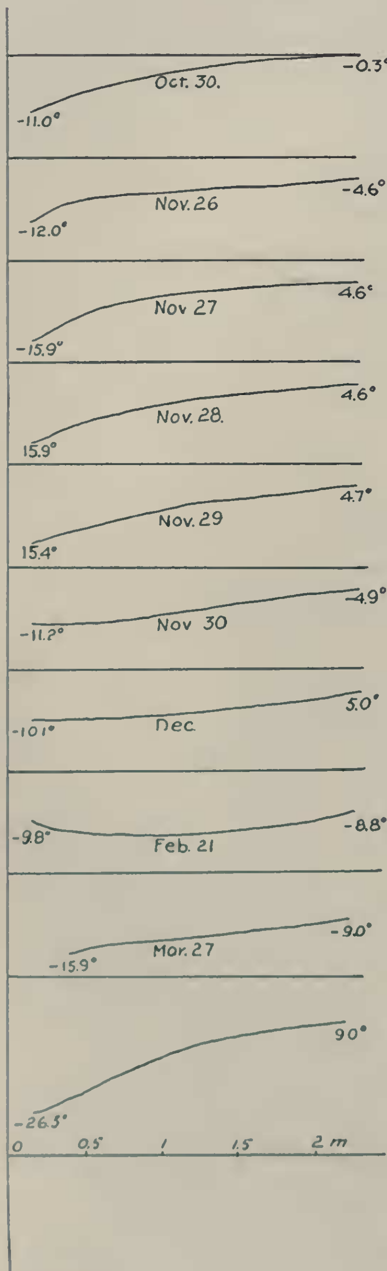

FIG. 33. Diagrams showing the distribution of temperatures within the surface zones of the inland-ice (after von Drygalski).[89]

von Drygalski within the western marginal zone, was found to have temperatures which in the winter season were normally lowest just below the surface, and which approximated to the zero of the centigrade scale at depths of generally a few meters only. In October with a sub-surface temperature of —11°C. the zone of zero temperature was reached at a depth of a little more than two meters. The sub-surface temperature steadily lowered from this time as the colder months came on, and the depth of zero temperature descended to below the limit of the experiments, which was only a little more than two meters. The form of the temperature curves in dependence upon depth showed clearly, however, that at very moderate depths equalization occurred. Late in March the lowest temperatures were reached with —26.3° C. for the immediate sub-surface temperature, and —9° C. for the temperature at depth of two meters. Warm weather at the surface resulted in a warm wave which descended through the snow, following the colder one, and so resulted in a maximum temperature not immediately below the surface but at increasing distances from it depending upon the duration of the warmer air temperatures at the surface. Thus, a ten day foehn in January raised the temperature at a depth of 2.2 meters, by a half a degree. It required over two days for this rise in temperature to proceed to a depth of 1 meter, and ten days for it to reach the depth of 2 meters. Similar effects are produced with the coming of the more prolonged warm weather of the summer season (see Fig. 33).

When the surface zone of the snow has reached the fusing point of snow, melting begins rapidly. Peary has drawn a graphic picture of the effect of the warm season upon the margins of the Greenland ice. Late in the spring the warmth of the sun at midday softens the surface first along the outermost borders of the ice, and this, freezing at night, forms a light crust. Gradually this crust extends up in the direction of the interior, and as the season advances the surface of the marginal rim becomes saturated with water. This zone of slush follows behind the crust towards the interior in a continually widening zone as the summer advances. Within the outermost zone the ice is so decomposed that pools come to occupy depressions upon the surface and streams cut deep gullies into the ice. At the same time the ice shows a more dirty appearance through the concentration of the rock débris due to the melting of its surface layers. By the end of the season, pebbles, boulders and moraines have in places made their appearance on the surface, and the streams have left a surface of almost impassable roughness.[90]

Differential Surface Melting of the Ice.—In his ascent of the western margin of the ice near the latitude of Disco Bay, Peary encountered lakes surrounded by morasses of water saturated with snow. The ice within this zone is crevassed, and down the fissures some of the surface streams disappear, at times in a large water-fall, and again in a "mill" of its own shaping. Baron Nordenskiöld

[89] E. von Drygalski, "Grönland-Expedition," *l. c.*, pp. 460–466.

[90] Peary, *Geogr. Jour.*, *l. c.*, p. 218. See also Nordenskiöld, "Grönland" (German ed.), pp. 125–138.

earlier observed almost identically the same phenomena along the line of his route. The intricate ramifications of the superglacial rivers and the occupation of almost the entire remaining surface of the ice by shallow ice wells and basins along his route are shown in Figs. 34 and 37.[91] These ice wells are in no wise restricted to inland-ice but are found in mountain glaciers as well, and represent but one of a series of allied phenomena dependent upon differential melting due to the presence of fine rock particles upon the ice. They were quite thoroughly described by Agassiz in his "Système

FIG. 34. Map showing the superglacial streams within the marginal zone of the inland-ice of Greenland (after Nordenskiöld).

Glacière." The particles of rock if not contiguous upon the ice surface absorb the sun's rays and cause excessive melting of the ice above and beneath them. They thus sink down into the ice and form dust wells (Fig. 35, *a*). The thin walls which separate those wells which are close together, being now attacked by the warm air on their sides instead of on the top only, they in their turn melt away to form a small basin, which soon either wholly or in part fills with water (Fig. 35, *b*). Where in contact with their neighbors and where of such thickness of accumulation as not to be heated through by the sun's rays, these rock particles behave in quite a

[91] A. E. Nordenskiöld, "Grönland," pp. 197–204, map 3.

different manner and protect the ice beneath them from the sun (note margins of wells and basins in Fig. 35, *a* and *b*). The same effect is brought about if the fragments are too large, for the thick-

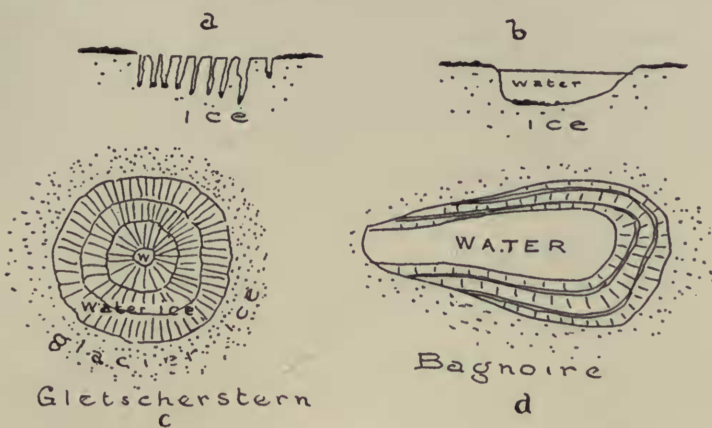

FIG. 35. Diagrams to show the effects of differential melting on the ice surface: *a*, dust wells; *b*, basins; *c*, glacier stars; *d*, bagnoires.

ness of surface layer of rock which can be sensibly warmed by the sun's rays is quite independent of the size of the fragment. Thus

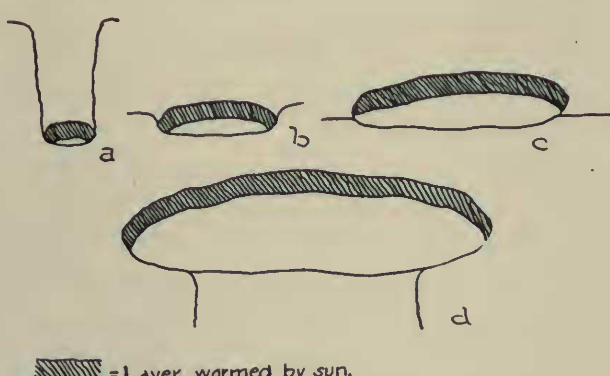

FIG. 36. Fragments of rock of different sizes to show their effect upon melting on the ice surface.

the familiar ice tables developed especially upon mountain glaciers are formed. Fig. 36 brings this out by showing the relation of the warmed surface layer to the whole fragment—(*a*) in a dust well, (*b*) in a pebble that sinks slightly into the ice until it reaches equilibrium, (*c*) in a slab of such size as to neither facilitate nor retard surface melting, and (*d*) in a large protective slab of rock.

The basins which result from the dust wells induce still other interesting structures. At night the water within these basins freezes in the form of needles which everywhere project inward from the steep walls of the basin. After repeated freezings the basins are often entirely closed by these needles and thus form "glacier stars" (see Fig. 35, *c*). Elongated basins have been given the name bagnoires (see Fig. 35, *d*).

From studies of such phenomena resulting from differential melting as developed upon the Great Aletsch glacier, we have found that the segregation of the rock débris upon the bottom of the basins later protects those areas after melting of the general surface has

FIG. 37. Section of the so-called "cryoconite holes" upon the surface of an ice hummock (after Nordenskiöld).

drained them of their water. Thus the familiar débris-covered ice cones come into existence and further increase the irregularities of the ice surface. The dust wells and basins which were described by Nordenskiöld covered over large areas the sides of steep hummocks in the ice as well as its more level surfaces (see Fig. 37).

On his return from his attack upon the inland-ice near Disco Bay, Peary travelled for seven hours through half-frozen morasses alternating with hard blue ice honey-combed with water cavities. Then the character of the ice completely changed, the slush and the water cavities disappeared, and the entire surface was granular snow-ice, scored in every direction with furrows, one to four feet deep, and two to ten feet in width, with a little stream at the bottom of each.[92]

Moats Between Rock and Ice Masses.—Wherever the ice sends a tongue down a valley, the edges of this ice shrink away from the warmer rocks on either side, thus leaving lateral canyons walled with ice on the one hand and with rock upon the other. Down these canyons are the courses of glacial streams.[93] An excellent example of such a lateral stream is furnished by the Benedict glacier (Plate XXIX, *A*).[94]

In most cases where nunataks project through the ice surface, the absorption of the sun's rays by the rock melts back the ice so as to leave a deep trench surrounding the island and much resembling the moat about an ancient castle. Snow drifted by the wind often bridges or partially fills the moat. Upon nunataks forty miles within the border of the ice in northeast Greenland the Danes found water running in the ravines and disappearing under the ice at the margin of the nunatak where it "formed the most fantastic ice-grottoes, where the light was broken into all colors through the crystal icicles." [95]

Such moats have been mentioned by nearly all explorers upon the ice. It has been claimed by von Drygalski that this phenomenon is characteristic of the west coast margin only, more ample nourishment upon the eastern coast making the snow rise about the rock like a water meniscus. In support of this view he cites Garde, who has figured such a case from the extreme south of Greenland.[96] Peary, however, has shown that the moats upon the west coast are often largely filled with snow.[97] Stein mentions this as a common feature after snow storms,[98] and Chamberlin[99] asserts that wherever

[92] *Jour. Am. Geogr. Soc., l. c.*, p. 282.

[93] Peary, *Jour. Am. Geogr. Soc., l. c.*, p. 286.

[94] R. E. Peary, "North Polar Exploration, Field Work of the Peary Arctic Club," 1898–02, Ann. Rept. Board of Regents Smith. Inst. for 1903, 1904, p. 517.

[95] Trolle, *Scot. Geogr. Mag.*, Vol. 25, 1909, pp. 65–66.

[96] "Die Eisbewegung," etc., *Pet. Mitt.*, Vol. 44, 1898, pp. 55–64.

[97] Peary, *Geogr. Jour., l. c.*, p. 217.

[98] Stein, *l. c.*

[99] Chamberlin, *Jour. Geol.*, Vol. 3, 1895, pp. 567–568.

the motion of the ice is considerable the trench does not appear, but the ice impinges forcibly upon the base of the nunatak.

Englacial and Subglacial Drainage of the Inland-ice.—In addition to the superglacial streams which are so much in evidence, others which are englacial run beneath the surface of the ice, as has often been discerned by putting the ear close to the ice surface. Nordenskiöld reports one instance where water spouted up from the surface mixed with a good deal of air and spray.[100] Salisbury also has mentioned a huge spring upon the surface of the ice in north Greenland that shot up to a distance of not less than ten feet above the bottom of the basin from which it issued. Owing to the fact that near the margin of the ice its surface is much crevassed, comparatively little water can continue to the border in surface streams. Salisbury mentions an instance where an englacial stream with a diameter of about five feet issued from the vertical face which formed the ice front. Most of the water flowing upon the surface descended, however, to the bottom and issued largely below the surface of the fluvio-glacial materials. It is, he says, a rare exception to find a visible stream issuing from beneath the ice at its margin. In most cases, the water undoubtedly comes out in quantities, though beneath the surface of the outwash apron, as could be detected by the ear.[101] Peary has observed that a greater abundance of water issues from beneath the ice-cap in extreme northeastern than in northwestern Greenland.[102]

The Marginal Lakes.—Wherever the ice has withdrawn from the rock surface and where ice drainage permits of it, small lakes marginal to the inland-ice have come into existence. Special interest attaches, however, to those bodies of water which are impounded by the ice itself along its margin, because of the light which is thrown upon the origin of somewhat similar bodies of water about the great continental glaciers of Europe and North America during late Pleistocene times. Attention was called to such ice-dammed lakes situated upon the margin of the Frederikshaab tongue of the inland-ice by the Jensen, Kornerup and Groth expedition of 1878.

[100] A. E. Nordenskiöld, "Grönland," p. 137.
[101] Salisbury, *l. c.*, pp. 806–7.
[102] Peary, *Geogr. Jour.*, *l. c.*, p. 224.

A map of this region was published by Jensen (see Fig. 38).[103] Here the lakes filled with water from the melting of the glacier by which their outlets are blocked, stand at different levels. The Tasersuak on the south standing at a level of 940 feet above the sea, is blocked by ice at both ends and is covered by bergs which are calved from the ice cliffs. This lake drains through a canal upon the ice to a much smaller lake standing at a level of 640 feet, and thence through a small river to the head of the Tiningerfjord. To the

FIG. 38. Map showing the margin of the Frederikshaab ice apron extending from the inland-ice of Greenland and showing the position of ice-dammed marginal lakes (after Jensen).

northward of the apron of ice another long fjord is blocked by a T-shaped extension of ice into its central portion. Thus there result two fresh water lakes standing at different levels, the lower one, like the Tasersuak, with ice cliffs at both ends, and the other blocked at one end only by the ice. A slight retreat of the inland-ice of this district would retire the T-shaped extension of the glacier, and the two smaller lakes would thus become united into one at the level of the lower. A still further withdrawal of the Frederikshaab

[103] "Meddelelser om Grönland," Heft 1. This map has been many times copied, best by Nordenskiöld in his "Grönland" on p. 161.

glacier tongue would open an outlet for this lake to the sea at a still lower level. Souvenirs of these events would be left in a series of parallel shore lines ascending in step-like succession to the head of the fjord (see Fig. 39). Suess has used this illustration to solve the

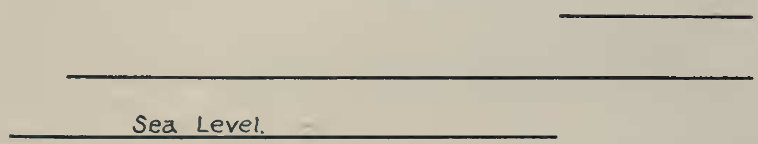

Fig. 39. Diagram showing arrangement of shore lines from marginal lakes to the northward of the Frederikshaab ice tongue, if its front should retire past the outlet of the lower lake.

vexed problem of the *seter,* the abandoned shore lines of Norway which have this peculiarity of arrangement.[104]

The famous "parallel roads" of glens Roy, Glaster and Speen in the Scottish Highlands, which have in similar manner vexed geologists but which were finally given a satisfactory explanation by Jamieson,[105] find here a living model. Still later a nearly identical example from Pleistocene times has been supplied from the Green Mountains to the eastward of Lake Champlain.[106]

About the Cornell tongue of the inland-ice of Greenland are many marginal lakes situated where the border drainage has been blocked by the glacier itself. These lakes have been described by Tarr, who says:[107]

> In its passage down the valley, between the ice and the land, the marginal stream finally enters the sea. During its passage it now and then encounters tongues of ice, and for a distance flows along them, and finally beneath them, where the glacier edge rests against a moraine, or the rock of the land. Again it falls over a rock ledge as a cascade, or even a grand waterfall; and every here and there it is dammed to form a marginal lake.

[104] Besides the Jakobshavn ice tongue, there is another lake confined in like manner to the Tasersuak. (Ed. Suess, "The Face of the Earth," Vol. 2, pp. 346–363.)

[105] Thomas T. Jamieson, On the parallel roads of Glen Roy and their place in the history of the glacial period. *Quart. Jour. Geol. Soc.*, Vol. 19, 1863. pp. 235–259.

[106] Because here the ice similarly blocked the natural outlet.

[107] R. S. Tarr, "The Margin of the Cornell Glacier," *Am. Geol.*, Vol. 20, 1897, pp. 150–151.

Dozens of these, great and small, were seen along the margin; and they varied in size from tiny pools to ponds half a mile in length, and 200 to 300 yards in width.

Since the water of the marginal streams is everywhere milky with sediment, these lakes are receiving quantities of muddy deposits, and in them tiny deltas are being built. Where the lake waters bathed the ice front little icebergs are coming off, in exactly the same way as in the fjord at the glacier front, and these are bearing out into the lake large rock fragments which are being strewn over the bottom or on the shores. Also at the base of the cliffs, as well as on some of the deltas formed by rapidly flowing streams, pebbles and boulders are being mixed with the clay.

Nearly every lake shows signs of alteration in level resulting from the change in outflow either to some point beneath the ice, when the lake may be entirely drained, or to some lower outlet for the lake opened by a change in the ice front, or by the down-cutting of the stream bed where it is eating its way through a morainic dam. The different elevations are plainly evident from the absence of lichens on the rocks, the clay clinging to the rocky shores, and the beach terraces along the old shore lines. In one case, at the western end of mount Schurman, a lake of this type, with a depth of at least 100 feet has recently been drained. Where these extinct lake beds exist one sees revealed an expanse of muddy bottom with scattered blocks of rock.

In Plate XXX, *A* and *B* are represented after Tarr, in the one case, one of the marginal lakes, and in the other, the formation of a delta under the conditions described. From the Karajak district on the northern side of the Upper Nugsuak Peninsula[108] von Drygalski has described in addition to the usual rock basin lakes left by the withdrawal of the ice front, a true ice-dammed lake which appears upon his map as the *Randsee*.[109]

No one of the marginal lakes thus far described furnishes a parallel to the interesting Pleistocene glacial lakes of the Laurentian basin of North America, since these developed for the most part upon a surface of relatively mild relief, and the shores not formed by the glacier itself were generally moraines registering an earlier position during the retirement of the ice front. Perhaps an existing example comes nearest to being realized in connection with those glaciers which descend the eastern slopes of the Andes and enter the great lakes impounded behind moraines of an earlier

[108] "The Cornell tongue is situated upon the southern side of the same Peninsula."

[109] E. von Drygalski, "Grönland-Expedition," Vol. 1, pp. 61–63.

extension of the same ice tongues.[110] In these cases the ice fronts of the glaciers are cut back into cliffs from which are derived the bergs that float upon the surface. The ice cliff and some of the bergs of Lake Argentino are shown in Plate XXX, *B*. According to Moreno, Lake Tyndall is bounded on the west by true inland-ice, the remnant of the larger sheet of Pleistocene times.

Ice Dams in Extraglacial Drainage.—In north Greenland outside the ice front, the brooks sometimes offer a striking example of ice obstructions forming by irrigation. This is often the case where their beds are wide and are covered with boulders. The water generally continues to run beneath the stones for a great part of the winter. Later, however, its outlets may freeze up, whereupon the water rises, inundating the stones and covering them with an ice crust. Through successive obstruction, overflowing and freezing of these streams, the ice dam which results may attain to such a thickness that it is still to be found at these places late in the summer when the ice and snow have elsewhere disappeared from the low land.[111] The significance of such dams as obstructions during a readvance of the ice front may well be considerable.

Submarine Wells in Fjord Heads.—Rink states that the sea flowing into the fjord in front of the glacier tongue which ends below the water level, is kept in almost continual motion by eddies not unlike those which are seen where springs issue from the bottom of a shallow lake. Such areas upon the surface of the fjord may generally be recognized by the flocks of sea birds which circle above them and now and then dive for food.[112] The existence of such fresh water streams as this implies may also be inferred from the strong seaward current that prevails in the fjords and which is so effective in clearing them of bergs. Such a whirlpool of fresh water or "submarine well" was observed by Rink in the Kvanersok-

[110] Francisco P. Moreno, "Explorations in Patagonia," *Geogr. Jour.*, Vol. 14, 1899, pp. 253–256. Also Hans Steffen, "The Patagonian Cordillera and its Main Rivers between 41° and 48° South latitude," *ibid.*, Vol. 16, 1900, pp. 203–206. Also Sir Martin Conway, "Aconcagua and Tierra del Fuego," London, 1902, pp. 134–135.

[111] Henry Rink, "Danish Greenland, Its People and its Products," London, 1877, p. 366.

[112] Rink, *l. c.*, pp. 50, 360–363.

fjord (lat. 62° N.) which was over 100 yards in diameter. The kittiwakes swarmed over the spot, and the water was muddy, although no brooks were observed along neighboring shores. This well Rink believed, from reports furnished by the natives, to be much smaller than the similar ones in some other fjords.

According to Rink[113] the lateral lake which borders the inland-ice of Greenland in one of the branches of the Godthaabfjord-Kangersunek, suffers changes of level just when the submarine wells before the ice cliff in the fjord showed marked changes in volume. Thus, whenever the water of the lake suddenly subsides, the submarine wells from the bottom of the fjord burst out with violence. On the other hand, when the water in the lake is rising, the wells are relatively quiet. These sudden discharges of the water from lateral lakes, save only that their outlet is submarine, seem to be in every way analogous to the spasmodic discharges of the Märjelen See upon the margin of the Great Aletsch Glacier in Switzerland. When, as occasionally happens, this lake empties through the opening of a passage beneath the glacier, the villages which are situated miles below in the valley are suddenly inundated with water.

Discharge of Bergs from the Ice Front.

The Ice Cliff at Fjord Heads.—Wherever the inland-ice reaches the sea in the fjord heads, and where it comes directly to the sea in broad fronts, as it does near Melville Bay, at Jokull Bay and on the north side of northeast Foreland, it is here attacked directly by the waves and is further undermined through melting in the water. The crevassing of its surface over the generally steep descents to the fjords, in a large measure facilitates the attack of the water upon the ice by offering planes of weakness similar to the joint planes in rock cliffs attacked by the sea on headlands. The fjords, though often quite narrow, are generally of great depth, so that although the ice cliff often rises to a height of several hundred feet, and in such cases must be assumed to descend to a depth below the surface of from five to seven times this distance, its base probably everywhere rests upon the bottom of the fjord. To this a possible exception

[113] Rink, *l. c.*

has been noted for the great Karajak glacier, of which a relatively flat front section may be assumed to be the surface of a floating portion[114] (see Fig. 40). To this interesting example of a floating glacier tongue in connection with the inland-ice of the northern hemisphere, we may recall the probably floating front of the Turner

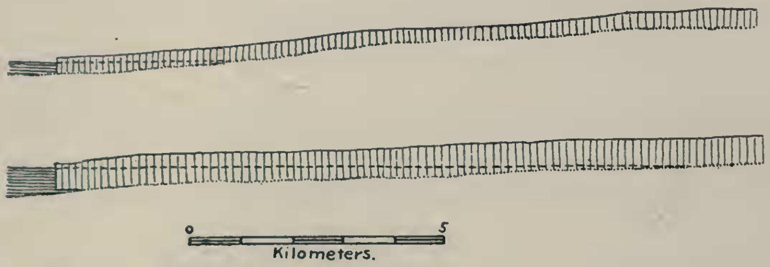

FIG. 40. Sections from the inland-ice through the Great and Little Karajak tongues to the Karajak fjord (after von Drygalski).

glacier, a dendritic glacier of the tide-water type in Alaska. For its type this example is apparently unique.[115]

Manner of Birth of Bergs from Studies in Alaska.—The birth of bergs from the parent glacier has been often described by travellers and the superlatives of the language have been drawn upon to express the grandeur and beauty of the observed phenomena. Simple as the process may appear to the casual tourist who makes the usual summer excursion to Alaska, it is not free from serious difficulties, and has given rise to conflicting views among specialists. The water in front of the ice cliff is generally so muddy, and the danger of approaching the ice front so great, that exact data are necessarily difficult to obtain. The smaller bergs composed of white ice, which are seen to fall into the water from the cliffs at almost all hours, offer no difficulties of explanation, but they are likewise without great significance as concerns the manner of formation of those great floating masses of ice which are carried far

[114] E. von Drygalski, "Grönland-Expedition," Vol. 1, pl. 43. See also R. D. Salisbury, The Greenland Expedition of 1895. *Jour. Geol.*, vol. 3, 1895, p. 885.

[115] R. S. Tarr, and B. S. Butler, "The Yakutat Bay Region, Alaska, Physiography and Glacial Geology," Prof. Pap. No. 64, U. S. Geol. Sur., 1909, pp. 39–40, pl. 10–a.

to sea and scattered over wide areas of the ocean before their final dissolution in the warmer southern waters.

The larger bergs instead of falling from the cliffs, suddenly rise out of the water as ice islands, often several hundred feet in front of the ice cliff. A wholly satisfactory solution of the problem of their birth involves a nice quantitative adjustment of several factors, all of which are undoubtedly more or less concerned. On the one hand, there is wave action which is effective especially near the water level and has a direct range of action extending from a distance below the surface equal to the length of a storm wave in the fjord, and to a height above the quiet level equal to the height of the wave's dash. If there were no melting in the water, and if the lower layers of the glacier moved forward as rapidly as the upper, the tendency would undoubtedly be to develop an erosion profile in every way like that of a rock-cut terrace upon the sea shore. With emphasis upon this element in the problem Russell has assumed that the ice cliff at the fjord is prolonged outward beneath the water as an ice foot which thins gradually toward the toe. Upon this hypothesis the bergs which rise from the water are born from the foot where the increasing buoyancy of the outer portion overcomes the cohesive strength of the material at the surface where rupture occurs. This view accounts particularly well for those bergs which rise from the water far in advance of the cliff (see Fig. 41).[116]

Laying stress rather upon melting in the water and upon the rapid forward movement of the upper layers of ice near the glacier margin, Reid has arrived at a wholly different conclusion concerning the origin of larger bergs:[117]

> The more rapid motion of the upper part would result in its projection beyond the lower part, and this would become greater and greater until its weight was sufficient in itself to break it off. The extent of the projection before a break would occur, depends evidently upon the strength of the ice. . . . That the ice for several hundred feet below the surface does not in general project farther than that above is evident from the fact that I have frequently seen large masses, extending to the very top of the ice front,

[116] I. C. Russell, "An Expedition to Mt. St. Elias, Alaska," *Nat. Geogr. Mag.*, Vol. 3, 1891, pp. 101–102, fig. 1.

[117] H. F. Reid, "Studies of Muir Glacier, Alaska," *ibid.*, Vol. 4, 1892, pp. 47–48.

shear off and sink vertically into the water, disappear for some seconds, and then rise again almost to their original height *before* turning over. If there were any projection within 300 feet of the surface this mass would have struck it and been overturned so that it could not have arisen vertically out of the water.

Fig. 41. Origin of bergs as a result especially of wave erosion (after Russell).

Reid thinks there are three ways in which bergs come into existence at the end of a glacier:

(*a*) A piece may break off and fall over—this is the usual way with small pinnacles; (*b*) a piece may shear off and sink into the water—this is the usual way with the larger masses; or, again, (*c*) ice may become detached under water and rise to the surface.

The supposed successive forms of the ice front, according to Reid, are shown in Fig. 42.

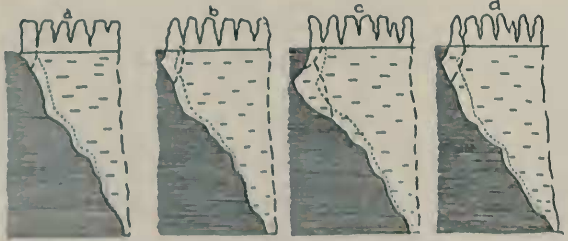

Fig. 42. Supposed successive forms of a tide-water glacier front (after Reid).

It is easy to see that Russell's and Reid's views might each apply in special cases dependent: (*a*) upon the narrowness or the sinuosities of the fjord, which would determine the reach of the waves; (*b*) upon the steepness of the slope back of the ice cliff, which would regulate the different velocities of surface and bottom layers of ice, and determine the measure of crevassing; (*c*) upon the irregularities in the floor of the ice tongue, which would largely fix the amount of shearing and overthrusting; (*d*) upon the presence or absence of warm ocean currents, which would regulate the rate of melting of the ice by the fjord water; and (*e*) upon the freezing of the water surface.[118] which must put a bar upon the action of the waves during the colder period.

Studies of Bergs Born of the Inland-ice of Greenland.—Though ice bergs are discharged from the inland-ice throughout practically the entire extent of the coast line of Greenland wherever inland-ice reaches the sea, yet the great bergs which push out into the broad Atlantic arise either on the west coast between Disco Bay and Smith Sound, or on the east coast south of the parallel of 68°. To the north of this latitude the bergs are firmly held in the heavy pack-ice, while the bergs of southwest Greenland form for the most part in such narrow fjords that they are too small to travel far before their final dissolution.

The size of the Greenland ice bergs has probably been much overestimated. Of 87 measurements made by von Drygalski on the large bergs calved in the Great Karajak fjord, the highest reached 137 meters above the water, or about 445 feet. This mass of ice was, however, against the glacier front, and probably rested on the bottom. None of the others measured were much above 100 meters high or about 325 feet.[119] The berg shown in Fig. 43, photographed by an earlier explorer in Melville Bay, measured 250 feet in height.

During fourteen months spent in the immediate vicinity of the steep front of the Great Karajak ice tongue, von Drygalski carried out extensive studies upon the calving of bergs, and has distinguished three classes. Those of the third class form almost con-

[118] R. S. Tarr, "The Arctic Ice as a Geological Agent," *Am. Jour. Sci.*, Vol. 3, 1897, p. 224.

[119] E. von Drygalski, "Grönland-Expedition," etc., *l. c.*, pp. 367–404.

stantly and consist of larger or smaller fragments which separate along the crevasses and fall into the sea. Only twice were calvings of the second class observed, namely, in late October and in early November. Of one of these von Drygalski says:

I heard a thundering noise, but at first neither I nor the Greenlanders who were with me saw anything. Suddenly a great distance away from the margin of the glacier, an ice berg emerged from the sea, rose out of the water, though not to the height of the cliff, and then moved away accompanied by a continuous loud tumult and by a rise in the level of the water, through the agency of which it moved away from the cliff quite rapidly. It did not come from the cliff, but certainly emerged from below. The Greenlanders, whom I afterwards questioned about it, gave me the same impression. . . . The margin of the glacier was unchanged.

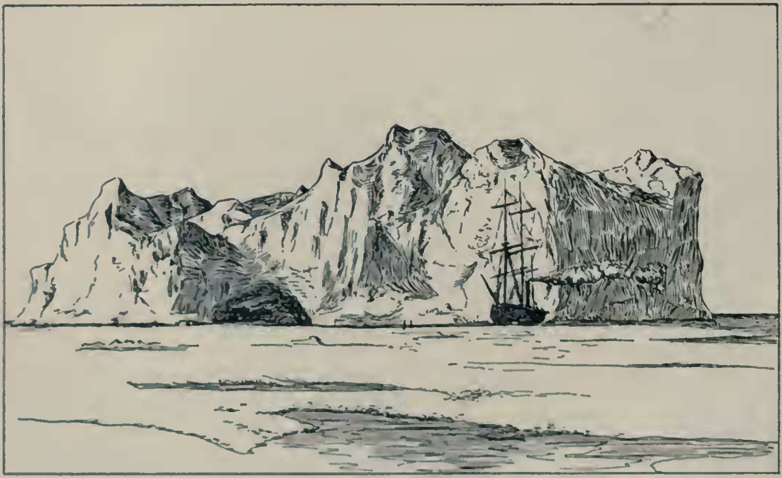

Fig. 43. A large berg floating in Melville Bay and surrounded by sea ice.

Here it was noticed that the berg was long though not as high as the ice cliff which terminated the glacier. It is the opinion of von Drygalski that bergs of this class come from the lowest layers of the glacier. Because of the pack-ice which in winter forms in front of the glacier, the ice cliff is at that time not cut away so fast, and it was, in fact, observed in the winter farther out than during the summer. This explanation in the main is in agreement with that of Russell.

Bergs of von Drygalski's first class, which are the most massive of all, separate from the entire thickness of the ice front. Two such bergs were observed in process of calving by von Drygalski and other members of his party. The same loud sound which had been heard at the birth of bergs of the second class accompanied the birth of those in the first class, *but the movement of separation from the glacier was visible at the same instant.* A portion of the cliff front was seen to separate from the cliff, being thereby thrown somewhat out of equilibrium and started in a pendular vibration which produced great waves in the fjord and increased slightly its distance from the newly formed ice cliff. It was here observed that the main pinnacle of the berg slightly exceeded in height the highest pinnacles of the new glacier rim. This, it will be remembered, is in contrast with the bergs of the second class which did not reach to the height of the cliff. Bergs of the first class usually regain their equilibrium after rhythmic oscillations and float away in an upright position. The bergs of the second class often turn over displaying the beautiful blue color of the lower layers. Salisbury's two types of Greenland icebergs seem to correspond with von Drygalski's bergs of the first and second classes.[119a]

The water waves which are sent out to the shores at the birth of a great ice berg extend 50 kilometers or more within the fjord, driving the smaller floating bergs together and thus assisting in their fragmentation and consequent dissolution. The calving of bergs of the first class von Drygalski believes occurs where the depth of the fjord has so far increased that the ice begins to leave the bottom and assume a swimming attitude. The buoyancy of the water is, he believes, thus the true cause of the separation of the bergs.

> Depths which are four to five times as great as the thickness of the inland-ice above the sea level, are not measured in Greenland in front of attached ice masses, because the latter become in that case broken up into ice bergs.[120]

This view gains strength from Salisbury's studies of the glaciers ending in Melville Bay and apparently floated for a very short distance back from their fronts and generally in the middle only.[120a]

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[119a] *Jour. Geol.*, Vol. 3, pp. 892–897.
[120] E. von Drygalski, *l. c.*, p. 404.
[120a] Salisbury, *Jour. Geol.*, Vol. 3, 1895, pp. 885–886.